DESIGNING A CELLULAR-BASED FULLY AUTOMATED CASE PICKING SYSTEM

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ABSTRACT

Order picking (OP) is the most expensive and labor-intensive activity in warehouses. Some authors argue that OP might be responsible for up to 55% of the operating costs in a warehouse. This might be more important for companies that handle large volumes of fast-moving commodities. Full-case picking processes and mixed pallet building are expensive and complex activities. Companies are looking for technologies to improve their efficiency and to reduce the operating costs of non-value added activities in their warehouses and distribution centers (DCs). Nowadays, the designers of order picking systems face great challenges due to increasing labor costs, less space and more frequent small orders with short delivery times. Consequently, there are constant research efforts devoted to finding new innovative full-case picking solutions that reduce operating costs, generate higher productivity, optimize space utilization and enhance customer service levels.

This dissertation presents a new fully automated case picking system (ACPS) called the Automated Cellular Case Picking System (ACCPS). The new system is characterized by the full and permanent accessibility of all stock keeping units (SKUs) in the system, which permits a strategic higher picking rate. This new system could be applied to different levels of automation within warehouses and DCs, and it is suitable for a wide range of warehouse automation requirements.

The proposed design consists of storage cells with the same design and operating principle as the vertical indexing case elevator, installed on one conveyor to form a storage line. Several storage lines are connected by a distributing conveyor from the inlet side and by a collecting conveyor from the outlet side, to form an ACCPS use-case model. The concept of this new system is based on the A-Farm concept, in order to create a new innovative dispensing and buffering system for cases.

ACCPS is a new concept for a full-case picking system that aims to provide better solutions for warehouses and DCs that deal with a high volume and low variety of products, which are handled in plastic crates or trays. ACCPS would be an efficient solution for many types of commodities such as (food, beverage, grocery, dairy, flowers, sausage, bakery and others). Optimizing picking processes, minimizing operating cost, and increasing efficiency are the most important aims of the new proposed design. This research investigates the layout, design, structure, costs, operating principles, cycle time, and throughput of the new system. A

simple logic process was applied to create a mathematical model in order to calculate the expected average time of the order picking and the throughput of this new ACPS.

A simulation model has been developed to aid in measuring the effectiveness of the ACCPS proposed design under real operating conditions. Two case studies have been used to evaluate the performance of the new system. Based on the real-time data of these two cases, many simulation scenarios were studied and analyzed in order to solve the storage assignment problem and to determine the best order picking strategy. Many optimization scenarios were simulated and analyzed in order to determine the optimum scenario.

In order to evaluate the ACCPS performance, a comparison was made between ACCPS and an alternative system with the same features. The alternative system, which is the most competitive system compared to the ACCPS, is the Gantry Robot System (GRS). The costs, throughput, and required areas were chosen as the main criteria for comparison between the two systems. The comparison confirmed the benefits of the ACCPS in decreasing the operating costs, required area, energy consumption, and the picking time. ACCPS also increased the space utilization rate and the throughput.

ACCPS provides a new technique for automating the full-case picking process (CPP) that contributes greatly to decreasing total operating cost by minimizing labor requirements, space requirements, and potential errors, and increasing productivity and efficiency. The structure of ACCPS, which is based on individual modules, can further increase the flexibility and the adaptability of the system.

ZUSAMMENFASSUNG

Der Kommissionierungsprozess (OP) wird als die höchst arbeitsintensive und kostenaufwändige Tätigkeit in den Lagern betrachtet. Einige Autoren behaupten, dass der Kommissionierungsprozess für bis zu 55 % aller Betriebskosten in einem Lager dafür verantwortlich sein könnte. Dies könnte möglicherweise wichtiger sein für Unternehmen, die große Volumina von schnell bewegenden Waren behandeln. Full-case-picking Prozesse und Mischpaletten von verschiedenen Produkten aufzubauen sind teure und komplexe Tätigkeiten. Firmen suchen nach Technologien, um ihre Leistungsfähigkeit zu verbessern und die Betriebskosten von zusätzlichen Tätigkeiten die keine Wertschöpfung erbringen in ihren Lagern und Distributionszentren (DCs) zu reduzieren. Heutzutage stehen die Designer der Kommissioniersysteme vor großen Herausforderungen, aufgrund der steigenden Arbeitskosten, weniger Platz und häufigere kleine Aufträge mit kurzen Lieferzeiten. Deshalb sind ständige Forschungsbemühungen gewidmet, um die Suche nach neuen innovativen Kommissionierlösungen für Stückgüter, die die Betriebskosten verringern, die Produktivität erhöhen, die Raumausnutzung optimieren und die Kundenservice verbessern.

Diese Dissertation präsentiert ein neues vollautomatisiertes Kommissioniersystem für Stückgüter (ACPS), das als automatisiertes zelluläres Case-picking-system (ACCPS) bezeichnet wird. Das neue System zeichnet sich durch die vollständige und dauerhafte Zugänglichkeit aller Lagerhaltung Einheiten (SKUs) im System, das einen strategischen höheren Durchsatz des Kommissionierungsprozesses ermöglicht. Dieses neue System könnte auf verschiedene Niveaus der Automation innerhalb von Lagern und DCs angewandt werden, und ist für eine breite Reihe von Lagerautomationsvoraussetzungen passend.

Das vorgeschlagene Design besteht aus Speicherzellen mit demselben Design und Betriebsprinzip wie der vertikale Senkrechtförderer für Stückgüter, der auf einem Förderband installiert ist, um eine Lagerungslinie zu bilden. Mehrere Lagerungslinien werden sich durch einen Verteilförderer von der Einlassseite und durch einen Sammelförderer von der Ausgangsseite verbunden, um ein ACCPS Use-Case-Modell zu bilden. Das Konzept dieses neuen Systems basiert auf dem Konzept des Schachtkommissionsystems (A-Farm), um ein neues innovatives System zum Zuführen und Puffern von Stückgütern zu schaffen. ACCPS ist ein neues Konzept für eine vollständiges Stückgütern Schachtkommissionsystem mit dem Ziel, bessere Lösungen für Lagern und DCs, die sich mit einer großen Menge und niedrigen

Vielfalt von Produkten befassen, die in Kunststoffkisten oder Tablare behandelt werden zur Verfügung zu stellen. ACCPS würde eine effiziente Lösung für viele Typen von Waren wie (Nahrung, Getränk, Lebensmittel, Molkerei, Blumen, Wurst, Bäckerei und andere) sein. Optimierung der Kommissionierungsprozesse, Minimierung der Betriebskosten und Steigerung der Effizienz sind die wichtigsten Ziele des neuen vorgeschlagenen Designs. Diese Forschung untersucht Layout, Design, Struktur, Kosten, Betriebsprinzipien, Zykluszeit und Durchsatz des neuen Systems.

Ein einfacher Logik-Prozess wurde angewendet, um ein mathematisches Modell zu erstellen, damit die erwartete durchschnittliche Zeit der Kommissionierung und der Durchsatz von dieser neuen ACPS zu berechnet werden. Ein Simulationsmodell wurde entwickelt, um bei der Messung der Effektivität des vorgeschlagenen Designs der ACCPS unter realen Betriebsbedingungen zu unterstützen. Zwei Fallstudien sind verwendet worden, um die Leistung des neuen Systems zu bewerten. Gestützt auf den Echtzeitdaten dieser zwei Fälle, viele Simulation Szenarien wurden untersucht und analysiert um das Problem der Lagerplatzzuweisung zu beheben und die beste Strategie für die Kommissionierung zu bestimmen. Viele Optimierung Szenarien wurden simuliert und analysiert um das optimale Szenario zu bestimmen.

Im Hinblick auf die Bewertung der Leistung des ACCPSs, wurde ein Vergleich zwischen ACCPS und ein alternatives System mit denselben Eigenschaften durchgeführt. Das Gantry Robot System (GRS), ist das alternative System für das am meist konkurrenzfähige System im Vergleich zum ACCPS. Die Kosten, der Durchsatz und die erforderliche Fläche wurden als die Hauptkriterien zum Vergleich zwischen den beiden Systemen gewählt. Der Vergleich hat die Vorteile des ACCPSs im Verringern der Betriebskosten, der erforderlichen Fläche, des Energieverbrauchs und der Entnahmezeit (Pickzeit) bestätigt. ACCPS stellt eine neue Technik zur Verfügung, um die Full-case-picking Prozessen (CPP) zu automatisieren, die außerordentlich zum Verringern von Gesamtbetriebskosten durch die Minderung von Arbeitskräftebedarf, Platzbedarf und potenziellen Fehlern, und die Erhöhung der Produktivität und Leistungsfähigkeit beiträgt. Die Struktur von ACCPS, die auf individuellen Modulen basiert, kann weiter die Flexibilität und die Anpassungsfähigkeit des Systems vergrößern.

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Thanks you all

Mohammed Ruzayqat

DEDICATED

To my parents

To my wife and kids

To my family, to my friends

and

To my homeland

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LIST OF ACRONYMS

ACCPS	Automated Cellular Case Picking System
ACP	Automated Case Picking
ACPS	Automated Case Picking System
AGV	Automated Guided Vehicle
AMHS	Automated Material Handling Systems
ASRS	Automated Storage and Retrieval System
BMH	Bastian Material Handling
CE	Create A European
CICMHE	College-Industry Council on Material Handling Education
CPP	Case Picking Process
CPS	Case Picking Systems
ERIM	Erasmus Research Institute of Management
GRS	Gantry Robot System
KPC	Kenya Pipeline Company
LGV	Laser Guided Vehicles
LIFO	Last In First Out
MFC	Material Flow Controller
OP	Order Picking
OPP	Order Picking Process
OPS	Order Picking System
PLC	Programmable Logic Controller
RFID	Radio Frequency Identification
ROI	Return on Investment
SCP	Schaefer Case Picking

SKU	Stock Keeping Units
STS	Schaefer Tray System
VIC	Vertical Indexing Conveyor
WCS	Warehouse Control Systems
WMCS	Warehouse Management and Control System
WMS	Warehouse Management Systems

LIST OF NOTATIONS

Acc^{Art}	**The accessibility of the article**
Acc^{ave}	**Average accessibility of any stored article within the cell**
$ACCPS^{costs}$	**Initial cost of the ACCPS**
$Ave.Nr.K.S\,_{one\ box}^{cell66}$	**Average number of kinetic steps for one crate along the retrieving path from cell66 to the output point**
$Ave.P.T\,_{one\ box}^{Model}$	**Average picking time of one crate**
$Ave.P.T\,_{one\ box}^{cell66}$	**Average picking time of one box (crate)**
$Ave.R.T\,_{first\ box}^{req.art}$	**Excepted average retrieval time of first crate of the required article stored in a multi-article cell**
Ax	**Number of vertical kinetic steps that the box of number i (Boxi) needs to reach the main conveyor**
a_x	**Horizontal gantry robot acceleration**
a_y	**Crane acceleration**
a_z	**Vertical gantry robot acceleration**
$\mathrm{Box_i}$	**Number of stored crates within the cell. According to their locations in the cell, the counting starts from the bottom, where i=1, 2, 3…**
Bx	**Number of horizontal kinetic steps on the main conveyor, which Boxi needs to reach the collecting conveyor**
C	**Investment amount (principal)**
C^{cell}	**Capacity of the cell**
$\mathrm{Cells.\,Energy}_{\mathrm{S/R}}^{\mathrm{cons/year}}$	**Energy consumption of the storage and retrieval process for all required crates per year**
C^{model}	**Capacity of the use-case model**
C_{nr}	**Total number of cycles per hour**
Cx	**Number of horizontal kinetic steps on the collecting conveyor, equivalent to the storage line width, which Boxi needs to reach the output point**
D^{de}	**Departing displacement of the wooden base within the de-palletizer**
D_{Exp}	**Depreciation expense per year**
D_R	**Depreciation rate**
d^{SA}	**Storage density of the storage area**
D_{st}^{tra}	**Traveling displacement of a stack on the distribution conveyor**
Dx	**Number of horizontal kinetic steps on the collecting conveyor equivalent to the maintenance hallway width, which Boxi needs to reach the output point**
$Energy_{cycle}^{cons}$	**Energy consumption per storage or retrieval process for one crate within the cell**

Ex	**Number of waiting steps, which Boxi needs to wait within the cell, due to conflict with advanced crates**
H	**Vertical crate displacement**
H^{model}	**Height of the use-case model**
H_{SA}	**Width of the effective storage area**
I	**Interest money**
k	**total number of stored articles within the cell**
L	**Horizontal crate displacement**
L_R	**Maximum vertical movement distance of the gantry robot**
L_{SA}	**Length of the effective storage area**
L_v	**Shifting distance of the I/O**
MH^w	**Width of the maintenance hallway**
$Min.Ave.P.T\,^{Model}_{one\ box}$	**Minimum average picking time of a crate from use-case model**
$Min.P.T\,^{cell66}_{Box_i}$	**Minimum picking time of an order from cell66, and the number of required crates in this order is equal to i**
$Min.P.T\,^{Model}_{Box_i}$	**Expected minimum OP time of an order where i is the total number of the required crates**
$min.R.T\,^{req.art}_{first\ box}$	**Excepted minimum retrieval time of the first crate of the required article stored in a multi-article cell**
$Nr^{art/pp}_{min}$	**Minimum number of articles that must be processed in one picking period**
$Nr.^{ave}_{crates/art}$	**Average number of stored crates per article**
$Nr^{Cells}_{min.req}$	**Minimum number of the required cells**
$Nr^{cells/line}$	**Number of storage cells per main conveyor or storage line**
$Nr^{cells/model}$	**Number of cells in the use-case model**
$Nr^{cr/pa}$	**Number of crates per pallet**
$Nr^{cr/st}$	**Number of crates per full-stack within the pallet**
$Nr^{\mathrm{handled.cr/day}}$	**Number of handled crates per year**
Nr^{MH}	**Number of maintenance hallways**
Nr^{Rep}_{max}	**Maximum number of replenishment processes**
Nr^{SL}	**Number of the storage lines in the use-case model**
Nr^{SL}_{min}	**Expected minimum required number of storage lines**
Nr_c	**Number of cycles or points that must be visited to pick the full capacity of the GRS robot based on the average number of the ordered crates per order-line**
$Nr.K.S\,^{cell66}_{Box_1}$	**Total number of kinetic steps for crate_1 along the retrieving path from cell66 to the output point (likewise for crate_2 and crate_10)**
$Nr.K.S\,^{cell66}_{Box_i}$	**Total number of kinetic steps for an order along the retrieving path from cell66 to the output point, where the number of required crates is equal to i, and i= 1, 2,…∞**

P	**Payment per year**
PV	**Present value**
$Pick_{Max}^{Cap}$	**Maximum pick capacity of the gantry robot per cycle**
R	**Interest rate per year**
SA^{l}	**Length of the storage area**
$SA^{min.req}$	**Minimum required area of the storage part**
SA^{w}	**Width of the storage area**
SC^{l}	**Length of the storage cell**
SL^{w}	**Width of the storage line**
T	**Period of the investment**
T^{de}	**Time of the departing interval for the pallet within the de-palletizer**
T^{fil}	**Filling time of the use-case model**
T^{in}	**Time of the input interval for the pallet within the de-palletizer**
T^{pro}	**Processing time of the de-palletizing intervals within the de-palletizer**
T^{sim}	**Simulation time of the OP**
T_{DC}	**Expected average double cycle time**
$\mathrm{T_{MC}}$	**Expected average multi-cycles time**
T_{SC}	**Expected average storage or retrieval (single cycle) cycle time**
$T_{pa}^{ave.dep}$	**Available de-palletizing time for a pallet**
$T_{w.b}^{de}$	**Departing time of the wooden base within the de-palletizer**
$T_{Total.Delay}^{Rep}$	**Total delay time caused by the replenishment processes**
$T_{Ave.Delay}^{Rep}$	**Expected average delay time between two replenishment processes**
$T_{Pa}^{Req.Dep}$	**Required time for de-palletizing a pallet**
$T_{dis.con}^{st.tra}$	**Traveling time of a stack on the distribution conveyor**
$T_{col.con}^{st.tra}$	**Traveling time of a stack on the collecting conveyor**
T_{crate}^{t}	**Total traveling time of the crate during storage or retrieval process within the boundary of the cell**
T_{OP}^{total}	**Total time of the OP**
$Thr_{filling}^{ave}$	**Average throughput of the filling process**
Thr_{model}^{ave}	**Average throughput of the model**
$Thr_{Retrieval}^{ave}$	**Average throughput of the retrieval process**
$Thr_{S/R}^{ave}$	**Average throughput of the storage and retrieval process at the same time**
$Thr_{Storage}^{ave}$	**Average throughput of the storage process**
Thr_{Max}^{GRS}	**Maximum throughput of the GRS use-case model**

$Thr_{dis.con}^{max}$	**Maximum number of stacks that the distribution conveyor can feed per hour**
$Thr_{cell/line}^{max}$	**Maximum throughput of the cell per line**
$Thr_{col.con}^{max}$	**Maximum available throughput of the collecting conveyor**
Thr_{model}^{max}	**Maximum throughput of the use-case model**
$Thr_{dep}^{min.req}$	**Minimum required throughput of the de-palletizer**
$Thr_{dis.con}^{min.req}$	**Minimum required throughput of the distribution conveyor**
Thr_{max}^{SL}	**Maximum throughput of a storage line**
$Thr_{max.req}^{system}$	**Maximum required throughput of ACCPS**
$Thr_{Total.Delay}^{System}$	**Total delayed throughput caused by replenishment processes**
t	**Total tolerance added to the width of every storage line in order to avoid conflict between the two storage lines, when they are installed back to back**
t_h	**Horizontal traveling time of the crate on the main conveyor**
$t_{P/D}$	**Picking/depositing time**
t_{Pos}	**Positioning time**
t_v	**Vertical traveling time of crate in the cell**
t_z	**Total time for the vertical travel time of the gantry robot in one cycle**
V^{de}	**Departing velocity of the wooden base within the de-palletizer**
$\mathrm{V}^{\mathrm{crate}}$	**Volume of a stored crate**
$\mathrm{V}^{\mathrm{crates/model}}$	**Used space volume of the stored crates**
V^{SA}	**Volume of the storage area**
$v^{dis.con}$	**Velocity of the distributing conveyor**
$v^{col.con}$	**Velocity of the collecting conveyor**
v_F	**Input/output conveyor speed**
v_h	**Horizontal crate velocity**
v_v	**Vertical crate velocity**
v_x	**Maximum horizontal gantry robot speed**
v_y	**Maximum crane speed**
v_z	**Maximum vertical gantry robot speed**

1 INTRODUCTION

This chapter gives a general background and describes the motivations for the research. The research problem is described, the objectives are identified, the research questions are formulated and the thesis outline is presented.

1.1 Background and Motivation

The efficiency and the effectiveness of a supply chain can be achieved by realizing the best possible performance of all milestones within that chain. 'Logistics' is defined as the effective and efficient management of the flow of goods and services between suppliers and consumers however, the transportation of raw materials, work in process, and finished goods from one point to another in a supply chain usually requires storage points –or warehouses– for varying periods of time. The warehouse thus plays a vital role in the supply chain (Edward, 2002). The location and the type of each warehouse determines its value within the supply chain. In recent times, the roles of warehouses have no longer been limited to storing or buffering products (raw materials, work in process and finished goods); they are more functional than they used to be. Nowadays, warehouses provide further value-added activities and services such as product consolidation, quality checking, final assembly, packaging, refurbishing (reverse logistics), and information services.

Several logistic activities take place in today's warehouses. Order picking (OP) is one of the core warehouse activities. This task is where the retrieval process of the order items from their storage sites takes place, so that the customer's request can be met. The order picking process (OPP) is a very labor-intensive process in manual systems and a very expensive one in automated systems (Goetschalckx and Ashayeri, 1989). It may consume up to 60% of all work activities in the warehouse (Drury, 1988). In a typical warehouse, the cost of the OPP may be as much as 55% of the total operating cost of the warehouse (Tompkins, 2010). Warehouse professionals therefore place strong emphasis on this activity in order to maximize the productivity of the process. The smoothness and economic performance of the OPS is one of the most significant goals for designers and managers of warehouses and Distribution

Centers (DCs). In summary, improving the OP capacity plays a vital role in reducing supply chain costs and in improving a warehouse's productivity.

OP can be executed manually, mechanically (semi-automated) or automatically (fully automated). In manual OPSs, the picker moves to the item storage locations in order to collect the items requested by customers (***picker-to-products***). In mechanical OPSs, the products are transported mechanically to the picker's position and the picker takes the requested items (***products-to-picker***). In automatic OPSs, the products are transported and picked up automatically without any manual effort (***picker-less***). While studies focusing on the first two types are easily available, there is a scarcity for the third type.

According to Dallari et al. (2009), high costs and limitations of the application area mean that automatic OPSs are more rare and therefore less studied. De Koster et al. (2007) argue that automatic and robotic picking systems are only used in special situations (e.g. when handling valuable, small or delicate items). Applied automatic OP solutions can be found in many areas nowadays, especially in full-case picking areas. Some of these solutions are semi-automated systems and others are fully automated. According to Gilmore and Holste (2009), there is a need for new innovative case picking solutions that are more efficient and more flexible.

Gilmore and Holste (2009) discuss in detail the reasons to invest in picking process automation, and provide a comprehensive view of a variety of automated systems. The systems available include a wide range of automated case picking (ACP) devices, including traditional "mechanized" case picking with auto-sorting, automated guided vehicle (AGV)/mobile robot-based case picking systems (CPSs), conveyor based solutions, vertical cascading order release system, gantry robot-based solutions, and automated storage and retrieval system (ASRS)-based CPSs. Invariably, the processes are tied together and underpinned by intelligent warehouse management systems (WMSs) and warehouse control systems (WCSs) that check on stock location management, material flow, and the whole order completion process.

In ACP, a machine that picks up the items or cases is necessary in order to collect the customer's order. This process is complicated and time consuming. While a few different case picking methods that can facilitate the procedure already exist, there are fewer solutions that completely replace humans in the OPP. Some solutions are better and more efficient than others. Optimizing the picking process is the goal for many researchers in this field. At present, many research studies improve the productivity level of the OPS by refining the operational policies (storage policies, picking policies and routing policies), and many other publications discuss the role of structural policies (e.g. layout policies, types of equipment and automation levels) in improving optimization levels. According to Goetschalckx and Ashayeri (1989), two types of factors play a fundamental role in designing and selecting the OPS. On the one hand, there are e*xternal factors*, which include marketing channels, customer demand patterns, supplier replenishment patterns and inventory levels. On the other hand there are *internal factors*, which may include system characteristics (mechanization level, information availability and warehouse dimensionality), organization, and operational policies. Operational policies may include storage allocation policies, picking strategies, and picker routing. Any new OPS should consider all these factors, and therefore designing the OPS is a very complex process. There are many strategies to improve the efficiency of an OPS. The diversity of these strategies can be seen in the literature, and includes such as:

- Different types of automated and manual OPSs.
- Different improvement times (during design phases or after installing the system (during the running phases)).
- Internal constraints such as: the stock keeping units (SKUs) nature, automation level, limitations of sources and management constraints.
- External constraints, including customer service level and market fluctuations.

1.2 Research Problem

Of the different picking forms (pallet picking, case picking and piece picking), the case picking process (CPP) is expensive and complex. Many companies are looking for technology to improve the efficiency and to reduce the costs of full-case picking and multi-SKU pallet building processes in their DCs (Gilmore and Holste, 2009). The designers of OPS therefore face great challenges, including: increasing labor costs, less available space and more frequent small orders with shorter delivery times. Consequently, there are constant research efforts devoted to new innovations that aim to reduce operational costs, generate higher productivity, optimize the space utilization rate and enhance service levels.

In general, case picking operations tend to have less diversity of product characteristics than piece picking processes, as they have fewer SKUs and higher picks per SKU. There are many automated systems to handle the CPP, and thus system design varies according to variables such as product type and packaging. This research describes new, innovative, fully automated and high-performance OPS for full-case picking, and the physical profiles of the SKUs in this new system are the crates or the standard boxes.

The requirements of modern OPSs include distributing and delivering materials quickly, in a timely manner, accurately and at minimum cost, and some automatic order picking systems have therefore been developed in order to meet these prerequisites. One is the Automated Cellular Case Picking System (ACCPS). ACCPS is a new concept of OPS, which allows for full-case picking, and aims to find better solutions for many warehouses and DCs. The ACCPS mainly deals with large volumes of products handled in plastic crates or trays. It has the ability to handle a variety of standard trays. As a full-crate picking system, ACCPS is typically applied to commodities such as food, beverage, dairy, flowers, sausages, and bread.

Currently, there are many facilities that face great challenges in applying automation, where no full or semi-ACP solutions are applied. This is because the efficiency and the effectiveness of the proposed solutions are unconvincing compared to the investment costs, required areas and picking rates. For example, in the grocery industry and for retailers, selecting an OPP is a great challenge that affects competitiveness. These circumstances push distributors to decrease costs, especially for non-added-value activities (such as the OP costs) and to increase the customer service level, especially delivery time. The grocery business is a large market as the product range is wide and material flows are massive, and so case picking is the most common OP type used in this area, because of the reduced diversity of characteristics and the uniform size of products, and the high picking rate per SKU. Taking this into consideration, a full-ACP solution is a convincing innovation in order to maximize profitability in this area, as well as in many and other related areas. Accordingly, this research presents a comprehensive analysis of a new innovative OP solution for full-CPP in warehouses and DCs, considering the OPS design and control procedures, in order to offer a fully-automated case picking system (ACPS).

1.3 Research Objectives

The purpose of this investigation is to study, analyze and design a new fully ACPS to increase the full-case OP efficiency within warehouses and distribution systems. The new idea improves performance in terms of case picking automation. A case picking operating principle that increases productivity and storage space utilization rate, reduces cycle time and operational costs and increases accuracy is also described. The proposed design in this research falls under the concept of the ASRS design problem, and so the focus is on enhancing the throughput and the utilization rate of storage space, as well as on reducing operating costs.

The ACCPS is expected to provide enhanced efficiency and flexibility to the CPP, and thus it meets the market requirements for several industries which produce high quantity and a small of variety products. In order to intensify analysis and to determine the optimal system design, this research investigates the properties, operating principles, construction, costs, cycle time and throughput of the new system. In order to evaluate the ACCPS performance, a comparison between the ACCPS and an alternative system with the same features has been conducted. The alternative system, which is in closest competition to the ACCPS, is the Gantry Robot System (GRS). The initial costs and the throughput are the criteria for comparison between the ACCPS and GRS. The proposed design of the new CPS has been described in detail in order to support the new system functions and operating principles. In this context, a simulation model based on two real cases has been developed to measure the effectiveness of the proposed system compared to the alternative existing system. Three performance variables are defined: *(1) throughput of the system, (2) space utilization rate, and (3) investment costs*.

1.4 Research Questions

Automation is a good solution with which to improve the competitiveness of operations by improving productivity, efficiency, quality and safety, as well as lowering costs (Groover, 2008). Many kinds of ACPS are therefore available for warehouses and DCs, and the core question is which one is the best. The most convenient way to answer this question is to conduct a comparison of the existing systems. In this context, the central assessment criteria are productivity, costs, cycle time, accuracy and flexibility. It is crucial in this analysis to reach a common understanding of these terms, and therefore, in a first step, their definitions are discussed, taking into account the corresponding context of each factor.

- ***Productivity*****:** refers to the pick rate, which can be expressed as cases per hour. There is a close relationship between productivity and accessibility to the required items. This means, that in order to raise the productivity, the accessibility should be increased. The best situation in this respect is the full accessibility of all the items in the system, however, the conflict between the retrieval process and the storage procedure (replenishment of the stock) is also closely connected to productivity. This means that there is an opportunity to increase the pick rate by harmonizing the storage and the retrieval processes during the operations.

- ***Costs:*** There are many kinds of costs. In the context of this research, the most important types of costs can be divided into fixed costs and operating costs. Fixed costs are the total costs of the system (e.g. investment costs required to build the system), the costs arising from the required space, and the costs of buildings (such as rent). The operating costs may include costs for labor, energy, maintenance and staff training. Typically, the fixed costs of automated solutions are high, but the operating costs are very low, and therefore, the decisive factor in the comparison is the rate of return in relation to the costs, also known as return on investment (ROI), which is a financial ratio intended to measure the benefit obtained from an investment.

- ***Cycle time:*** This term refers to the time an order takes from its entrance to the system until it reaches the shipping area. The cycle time has a close relationship with the customer service level and thus with customer satisfaction. This is due to the fact that customers usually expect timely delivery. The OP time is not the only factor that effects the cycle time, however, there are many other factors such as palletizing time, transportation time within the whole process and also the packaging time. Storage and picking strategies have a substantial effect on the cycle time.

- ***Accuracy:*** Accuracy could be defined as the system's ability to avoid errors occurring while the processes are running, especially in OP procedures. It has a great effect on customer service level. From a customer's point of view, delivery service can be defined as the right product being delivered to the right place at the right time (without errors), whereas for suppliers, errors translate into increased operating costs. In order to decrease the operational costs in a warehouse, the accuracy of the processes thus needs to be improved. The potential for enhancement thus depends on the proportion of the desired improvement, and for fully automated systems the accuracy ratio might approach to 100%.

- ***Flexibility:*** Flexibility can be defined as the ability of a system to adapt to a wide range of operating conditions. There are thus many aspects of flexibility. For example, increasing the number of SKUs, physical changes on SKUs, fluctuations of orders, growth requirements, and other factors can affect the flexibility level.

The research questions for each assessment criteria are the following:

Productivity: As explained above, productivity is closely linked to accessibility to the respective items as well as to the matching of the storage and retrieving processes. In this context, the operating strategies (such as storage policies and picking policies) play a substantial role in increasing the productivity of the system. The research questions involved with this part of the process are:

- ***Which mechanical design, operating principle and controlling principle satisfies the defined requirements in the best way?***
- ***How can the productivity be calculated?***

In order to answer the second question, a simple logic process is applied in order to develop a mathematical model. This mathematical model is developed in order to calculate the throughput of the system.

Costs: Taking into consideration the different types of costs and the importance of the ROI (which expresses the benefits derived from an investment), the research questions related to costs discussed in this research area are:

- ***What is the total cost of the system and what is the cost calculation method?***
- ***What are the possible ways to decrease fixed and operating costs in the new system?***

Basically, the costs of any system depend on its size, and therefore real-time data from an existing company is applied in order to build an accurate case study. The parameters of the use-case model are determined and the use-case model is created in accordance with the logistics requirements and the environmental constraints on operations.

Cycle Time: As explained previously, the cycle time is closely linked to the customer service level and thus to customer satisfaction, however, there are several factors that influence the cycle time (e.g. the time needed in OP, palletizing, transportation within the system and packaging). The storage and picking strategies also have a substantial effect on the cycle time. The research questions considered are thus:

- ***What are the best storage and picking strategies?***
- ***What is the effect of each strategy?***

In order to answer these questions, a simulation model was built and two real-time datasets were taken and analyzed in two actual case studies. Many scenarios were tested and the results of these tests are discussed and analyzed.

Flexibility: as explained previously, flexible systems should be able to deal with all operating conditions that have an expected effect on other relevant factors such as productivity, costs, cycle time and accuracy. The related research questions are:

- ***What aspects of flexibility should be considered during the designing process?***
- ***How can the system be made flexible considering the changes caused by operations?***

In answering these questions, and evaluating the new system, many aspects of flexibility are discussed and compared with an alternative system.

1.5 Research Outline

Figure 1.1 illustrates the thesis structure, where this thesis consists of seven chapters. Chapter 1 introduces and describes the background of the research area and presents the aims, objectives and questions for the research. In Chapter 2, the theoretical background of the OPP in introduced. Focus is placed on its main role, the different types of OPSs and their classification. A comprehensive literature review on strategies for improving OP efficiency, automation solutions and the ACPS design problem is presented. In Chapter 3, the new system (ACCPS) is described and analyzed in detail (design requirements, structure developments, operating principles, and control and management system). In Chapter 4, the case-study model’s parameters are determined, the mathematical model is generated, and the most important calculations are executed.

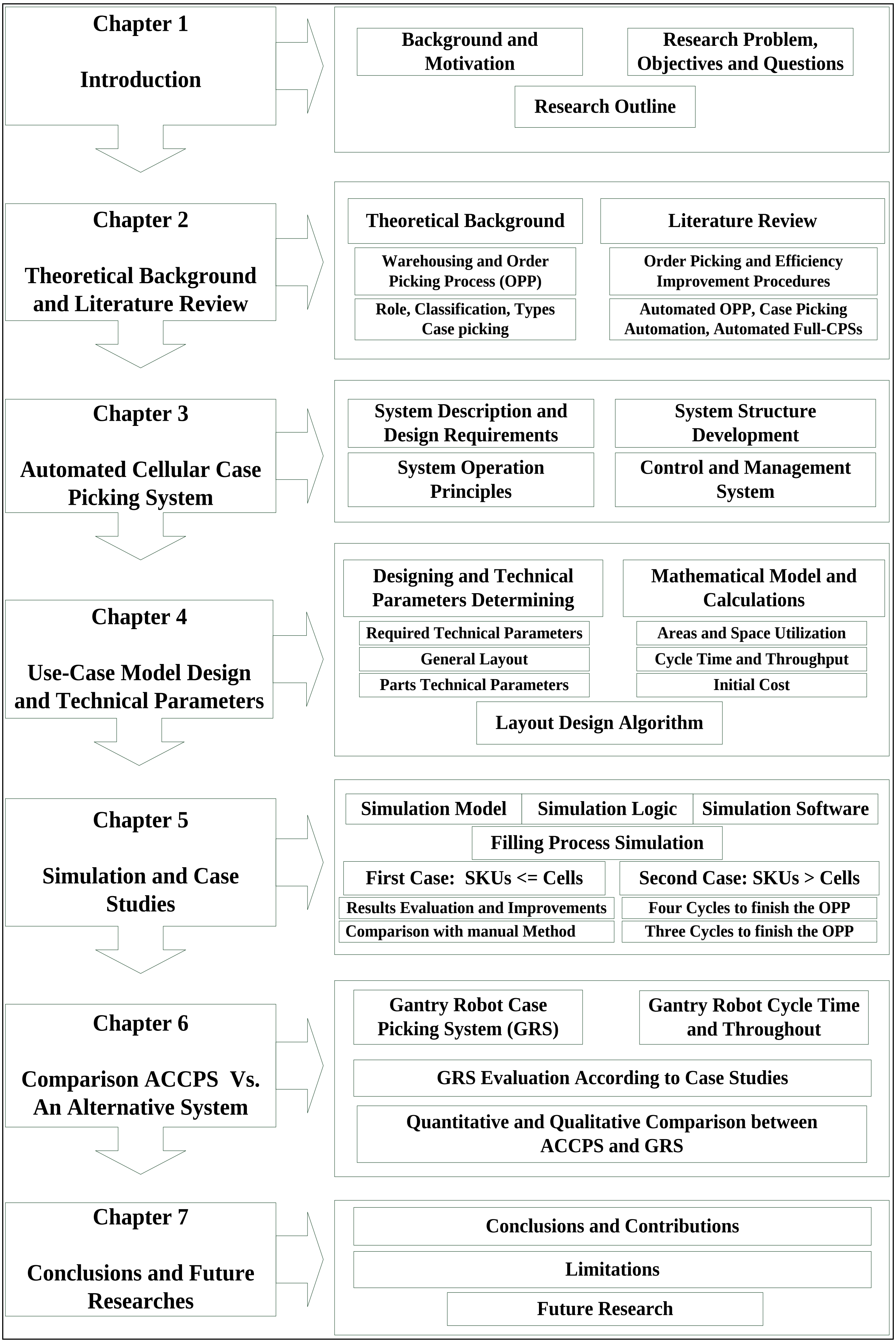


Figure 1.1 Thesis structure

The simulation model and the two case studies are presented in Chapter 5. The most important scenarios will be tested and discussed based on these two real cases. At the end of this chapter, the results are evaluated and the improvements are discussed. In Chapter 6, a comparison between the new system and other alternatives is made in order to obtain an extensive evaluation of the new system. Finally, Chapter 7 concludes, and discusses the contributions and limitations of the research. It will also give an outlook for future research opportunities.

2 THEORETICAL BACKGROUND AND LITERATURE REVIEW

This chapter is divided into two parts: the first is a background presenting the basic terminologies of OP and warehousing systems and presents the state of the art. This part presents our basic knowledge about the OPP, the role of the OPP in logistics, classification, types and is also about the CPP. The second part presents an overview of the major developments of the ACP problem. Efficiency improvement procedures and case picking automation concepts and systems are presented. Studies related to automation justification, limitation, risks and also the basics of OPS design and automation solution are presented.

2.1 Introduction

Many logistics managers turn to automation to boost DC efficiencies, and make an effort to ameliorate amalgamation between automated systems and human capital for the whole order satisfaction and accomplishment of operation, which will contribute a high number of productivity and also reducing time, however, there is an increasing number of SKUs and shorter product life cycles in industries. It is thus absolutely necessary for numerous warehouses to create more rapidly systems as well as operating strategies. This section gives a comprehensive description and analysis of OPP. The background of OPPs, automated warehouses and full-case picking are introduced.

2.2 Theoretical Background

Optimizing the design of the OPS plays a significant role in solving complex picking processes. From an organizational perspective, each OPP can instantly impact productivity and turnover in DC. Since the design issue of the OPP is the most common practice used, there are many case studies. The problem has been studied by many logistic researchers in order to determine the best OPS. Several simplifying assumptions have been made that could identify practical correlations between practice and academic research. The main objectives within OP operation are to reduce the throughput time for an order, to make sure the warehouse space is utilized in an optimal way and to achieve a minimum cost for the picking system.

Many companies have a strong interest in developing a new generation of highly efficient and multi-factor system OPSs. Improving customer service quality and minimizing global cost through the implementation of flexible OPS is another target (Manzini et al., 2005). Considerations in designing layout, storage capability, type of order release system, routing and sorting systems should result in excellent OPS. This is important in determining the exact amount of the right product to be transferred to right place according to customer orders. De Koster et al. (2007) have defined OP as a process to assemble, and to organize within a specific time, based on customer orders, placing the stock directly in order-lines, releasing the order downstream and providing a picking process at the right place at the right time. In other words, OP can be defined as order fulfillment, from withdrawing items from storage to satisfying a number of customer orders.

An OPS drives both overall logistics costs and the service levels to be provided to the customer. Dallari et al. (2009) proposed a new methodology for designing the OP system. There are four main stages of succession, the early stage is an input stage followed by a selection stage, evaluation stage and finally a detail stage. Generally, genetic algorithms are used to support decision-making at an early stage in designing OPS. A genetic algorithm is an optimization that uses genotypes in a population. Khojasteh-Ghamari and Son (2008) explained that each genotype represents a potential solution to a problem. This method is thus executed based on an evaluation process through a population of chromosomes, and has been developed to carefully and thoroughly search a space of potential solutions. In other words, each chromosome in each generation has been evaluated, a new population is selected according to the probability distribution and the chromosomes in the new population are recombined by mutation and crossover operators. The best chromosome would then represent the optimum solution.

There are two ways in which the process of retrieving items when OPSs are applied. The first way is that load of a single-unit is retrieved and the second way is that load of multiple-unit is retrieved. It is therefore important for every designer to choose the right method before starting the problem solving process for an OPP. OPPs can be classified into two parts. OPPs may employ humans or machines. In picking systems that use human pickers, items may actually be picked based on two methods, picker-to-part or part-to-picker. Picker-to-part can be configured to have high capacity for manual work; and part-to-picker is characterized by the use of ASRS or a carousel system.

Manzini et al. (2007) explain that the rapid growth of the level of the supply chain has placed downward pressure on many DCs. They conducted research to design class-based storage, with efficient performance based on picker-to-part. The combination of dynamic simulation, genetic algorithm and statistical analysis could be the best alternative in order to design excellent OPS. Chang et al. (2007) suggested the optimization of the OP could be improved by the adoption of newer automated picking solutions. For this reason, many companies put effort into development from OPS to an automated picking system.

2.2.1 Warehousing and distribution center

According to Bartholdi III and Hackman (2010), the warehouses can be defined as the points in the supply chain where a product pauses, to better match supply with customer demand, or to consolidate products to reduce transportation costs and to provide customer service. 'Warehousing' refers to the activities involving the large-scale storage of goods in a systematic and orderly manner, and making them conveniently available when needed (Achieng and Rotich, 2013). Actually, there is no difference between a warehouse and a DC as a physical system, the main difference is that while the warehouse focuses on storage methods, the DC focuses on the most efficient and cost effective customer order fulfillment methods. A DC can be defined as a facility that is used for the receipt, temporary storage, and redistribution of goods according to customer orders as they are received. The three main types of warehouses are (Van den Berg and Zijm, 1999):

- *Distribution warehouses* (products from one or many suppliers to many customers).
- *Production warehouses* (for raw materials, semi-finished products and finished products in production plant).
- *Contract warehouses* (servicing one or more customers).

According to Rouwenhorst et al. (2000), the main warehouse activities can be classified in four stages according to the material flow principle:

- *Receiving*
- *Storage*
- *OP*

- *Shipping*

Rouwenhorst et al. (2000) propose three stages of decision-making to solve the warehouse design problem, these stages have three directions of classification (organization, resources and processes):

- *Strategic stage*: at this stage the strategic warehouse requirement should be determined, such as location, size, interim and futurism investment cost, dimensions of future growth, etc. Normally this level of decision has a long term impact. In this stage the flow process is designed and the types of technical systems are selected.
- *Tactical stage*: at this stage the system details should be determined, such as the dimensions of all system areas and parts, layout design, equipment selection, organization designing, etc. Typically, this level focuses on the dimensions of resources and on the determination of a layout and a number of organizational issues.
- *Operational stage*: in this stage the operational and the interfacing constraints between the resources and the operators should be determined so as to design the best organization and operating policies.

According to Van den Berg and Zijm (1999), the OPSs within the warehousing systems, can be classified into three main types according to the automation level:

- *Manual warehousing systems (picker-to-parts)*
- *Automated warehousing systems (parts-to-picker)*
- Automatic warehousing systems (picker-less systems).

Most of the warehouses or DCs are divided into two main areas. The first one is where the SKUs are stored in large quantities (bulk storage) and it is called a reserve area. Normally, the physical SKUs in this area are pallets with a low turnover inventory rate. The storage and retrieval process in this area can be manual or automated. Usually this area has a high space utilization rate. The second main area contains three sub-areas: a case picking area, a broken-case picking area and a consolidation area. Usually this area has a high automation level, high inventory turnover rate and high investment cost. Otherwise, it is the focus of most DC managers in improving the efficiency and effectiveness of the system. It plays a significant role and has a direct effect on the customer service level. The main functions and flows of a warehouse or a DC, based on Tompkin's (2010) classifications, are explained in Figure 2.1.

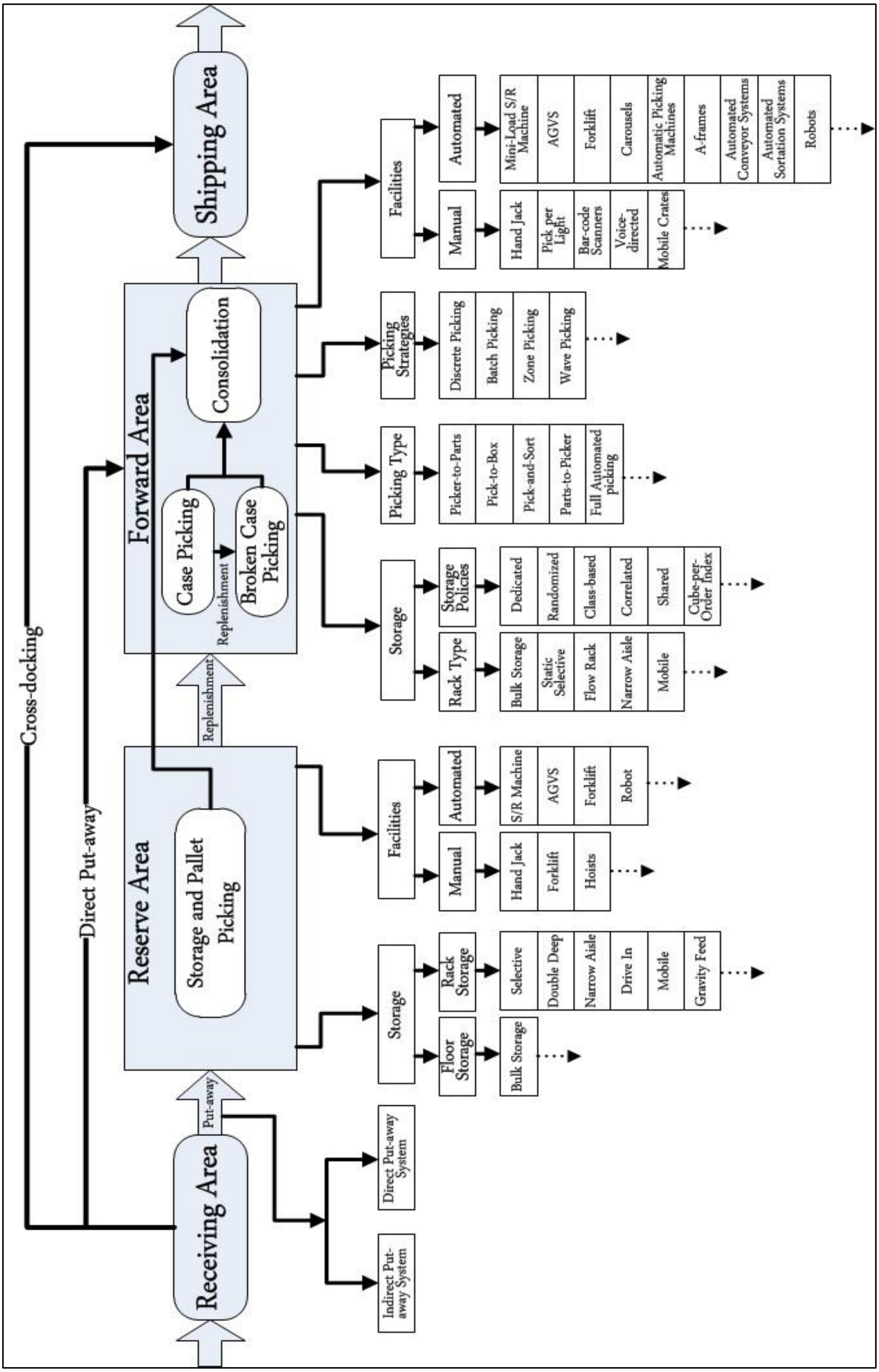


Figure 2.1 Warehouses and distribution center activities, flows and other aspects

2.2.2 Significance of the OPP

According to Dukic and Oluic (2007), the OPP can be defined as the process of retrieving items from storage locations in response to a specific customer request. It is the most important activity in the warehouse and DC, and is the focus of most warehouse managers, developers and designers in respect of improving the efficiency and the effectiveness of the warehouse and DC. According to Dukic and Oluic (2007), 90% of total operating time, and according to Drury (1988) 55% of operating cost, go to the OP activity in conventional warehouses. This process may involve as much as 60% of all labor activities in a warehouse, and may account for as much as 65% of all operating expenses (Gademann and Velde, 2005).

Today there are many order picking concepts and technologies available, and many solutions to executing OPP for increased productivity, increased throughput and to improve accuracy, but still there is a great need for more improvements, more automation, more strategies and more solutions. The biggest challenge facing OPS users is still selecting the best system, the best technology and the best solution for their processes. Order processing is related to martial and information flows between customers and suppliers. Customers have to request the products in some way (orders). These orders are transmitted to the suppliers. The availability of the requested items is verified, then the requested items are picked up, packed and delivered to their destinations with their shipping documents. The invoice is sent directly from the supplier to the customer and they have to be kept informed about the status of their orders (see Figure 2.2).

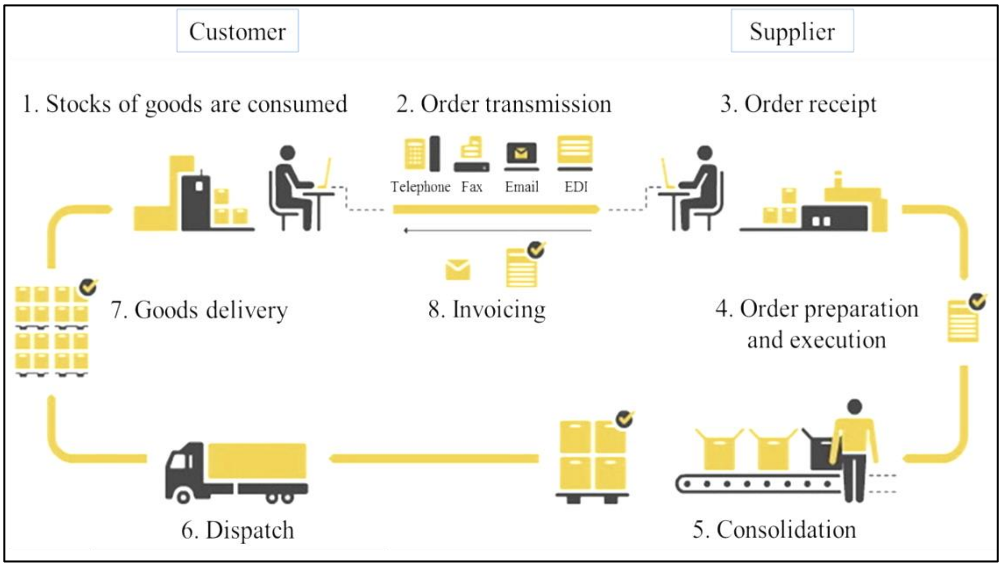


Figure 2.2 Main phases of the order process (DHL Discover Logistics, 2014)

So as to understand the procedures of OPP the order picker activities should be clear. An order picker (person in manual system or machine automated system) always starts and ends the cycle at a point which is called the Pickup and Deposit (P/D) point. The picker gets the information about the requisite items, travels to the locations, searches for and finds the correct position, extracts the items, returns to the original point and deposits the load there, then starts a new cycle. The trip of the picker can be long, and take a long time. This time depends on the OP policies, storage policies, warehousing technologies, warehouse layout, and warehouse automation levels. In a typical warehouse the order picker can walk six miles a day. The breakdown of warehouse activity costs by rate may be, for example:

- *Shipping: 20%*
- *Receiving: 10%*
- *Storage: 15%*
- *OP: 55%*

The time spent on activities related to order picking is equal to 75% of the total time that spent in the warehouse. The result of value stream mapping for OPPs is as follows

- *10%: searching* (which is non-value-added)
- *5%: writing* (which is non-value-added)
- *25%: picking* (which is value-added)
- *60%: walking* (which is non-value-added)

Here only 25% of the order picking time is considered as a value-added time, and 75% of this time is considered not value-added. OPP is therefore an important problem for most warehouses and has great optimization potential (Palevich, 2011).

2.2.3 Role of OPP in logistics

Planning, controlling and organizing material flows and the information related to this flow is known as ‘logistics’. Logistics is one of the most important activities in modern society. Logistics systems are made up of three main activities: order processing, inventory management, and freight transportation (Ghiani et al., 2004). In recent years the nature of OP has changed considerably. The demand on automated OPSs within logistics operations has increased under the effect of a number of different factors, such as the dramatic increase in online shopping, the constant desire to reduce inventories and pick items more frequently and in smaller quantities. This means that the OPP has become an increasingly cost-intensive function. OPP is a process which can be seen in all types of logistics hubs. It is characterized by high labor and needs highly efficient control and organization systems. In most warehouses and DCs, the key task is to implement the orders from customers as soon as possible and at the lowest possible cost. For this purpose, it is necessary for permanent control and attention to ensure that the processes and activity picking implemented in these facilities is efficient, fast and accurate. The process of completion is defined as the set of logistical, operational and organizational activities, which resulted in the organization of assortments of goods in accordance with the orders in the system of internal storage, drawn up on the basis of orders of recipients. Due to strong competitive pressure, warehouses and DC managers seek opportunities for improvement at every stage of a product’s flow within the supply chain.

According to Langen (2001), OPP can be considered as the center of the warehouse logistics, because it has a direct and significant impact on many other areas, such as production, distribution, etc. The globalization of markets, the increasing quality requirements, the increasing competition and cost pressures and dynamics of demand are issues that affect the everyday life and the field of action of a company with respect to logistics. The OPSs nowadays provide an important key element in the economy, since they significantly influence logistics costs and delivery (Galka et al., 2008). Logistics costs are about 15% of the turnover, and OPP costs are about 5% of the turnover (PulvericH and ScHietinger, 2009). Kearney (1984) estimated logistics costs in the USA, and found that overall they are about 21% of the gross national product, and that 28% of these costs are for storage and picking systems. This means OP is a major cost component of warehouse operations and has an important impact on a supply chain’s efficiency (Coyle et al., 1996). The total logistics cost in Europe in 2005 was about 800 billion Euros, and in 2010 was 930 billion Euros. The warehousing costs were 24% of the total (Klaus, et al., 2007 and 2011) see Figure 2.3.

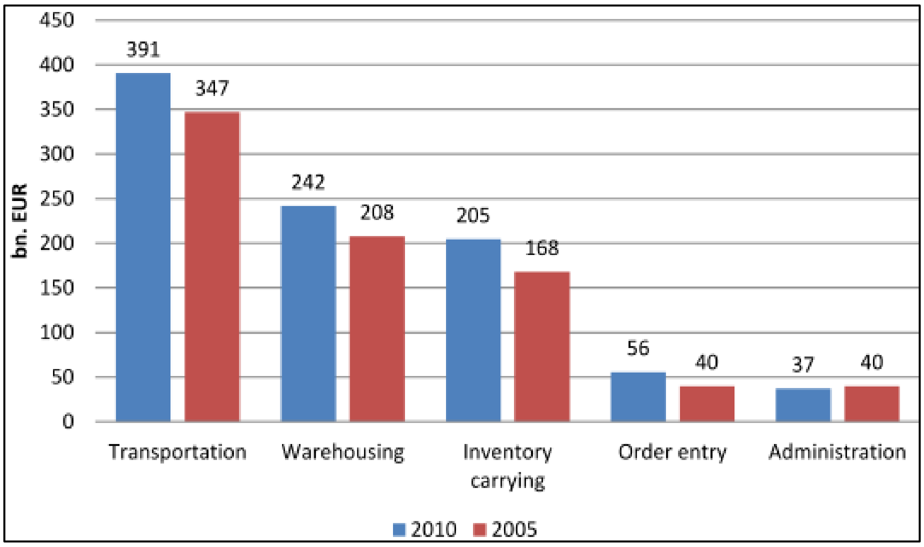


Figure 2.3 Logistics costs in Europe in 2010 and 2005, (bn. EUR: billion Euros) (Klaus et al., 2007; 2011)

The proportion of OP costs in the total logistics cost is estimated by multiplying the OP cost ratio (from the total warehousing costs) by the ratio of warehousing costs from logistics costs. The OP cost as part of the total logistics cost is equal to 15.6%.

2.2.4 Classification of OPSs

There is no currently available classification of OPSs that is inclusive of all systems. Due to the different classification bases, there are many classification methods for order picking systems. Recently De Koster et al. (2007) reviewed a classification based on the dynamic items in the system, where there are two main categories based on the employment of humans and machines within the order picking system (see Figure 2.4).

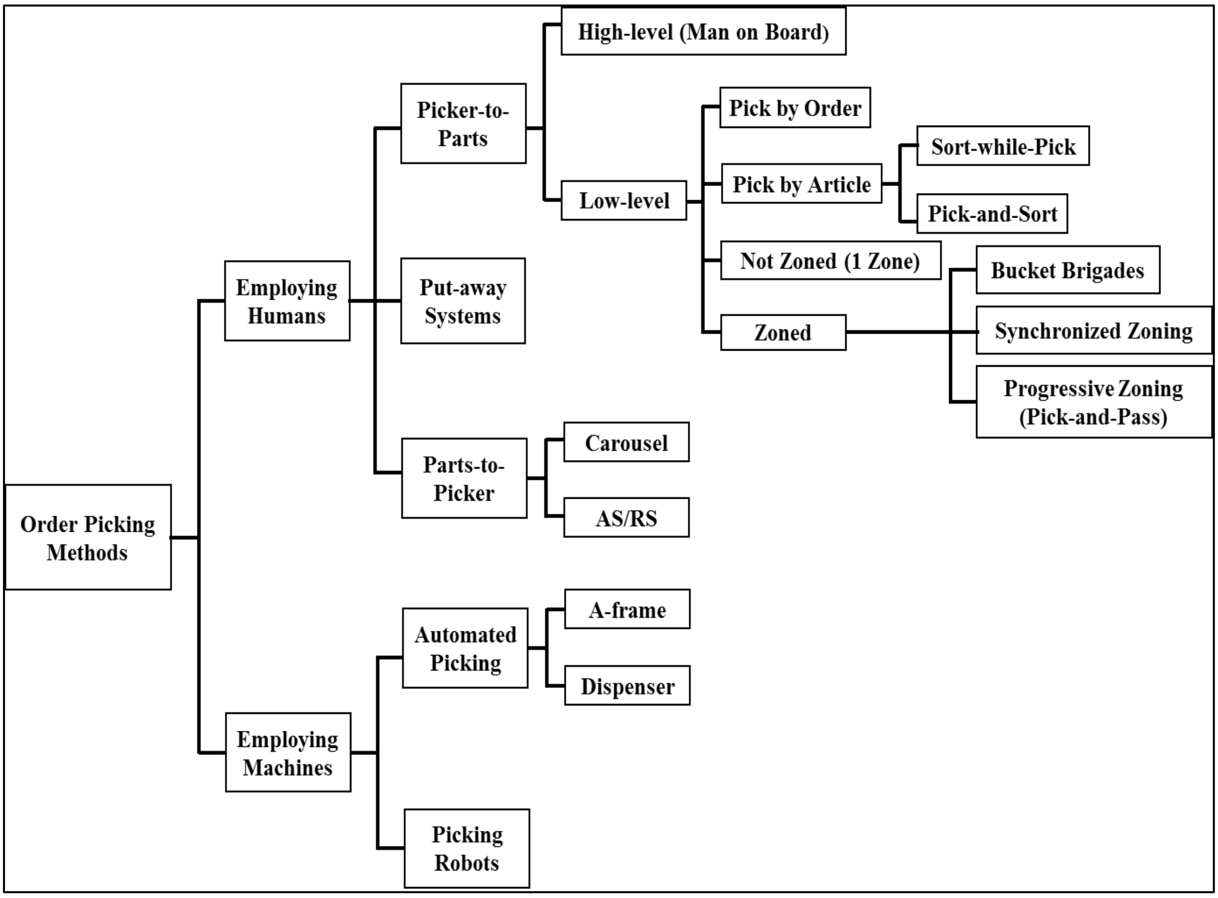


Figure 2.4 Classification of the OPSs according to De Koster (De Koster et al., 2007)

Dallari et al. (2009) later proposed a new classification based on the four main decisions: who picks the goods (humans/machines), who moves in the picking area (pickers/goods), whether conveyors are used to connect each picking zone, and which picking policy is employed (picking by order or by item) see Figure 2.5.

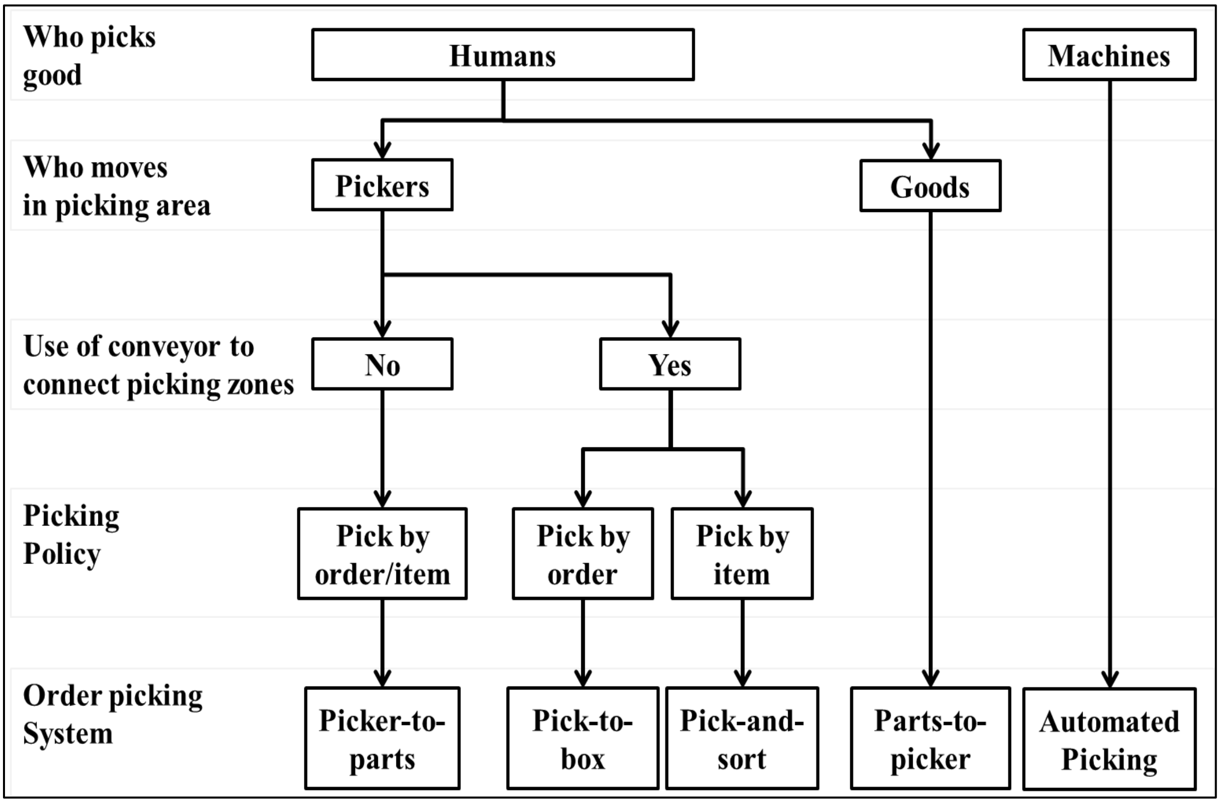


Figure 2.5 Classification of the OPSs according to Dallari (Dallari et al., 2009)

Based on the classification methods of De Koster et al. (2007) and Dallari et al. (2009), any OPS normally contains six main parts, and the classification of OPS can be made based on these six parts and the relationships between them, as illustrated in Figure 2.6. These parts are as follows

- *P/D point (pick-station/dynamic or static)*
- *Picker (human or machine/dynamic or static)*
- *Rack system (dynamic or static)*
- *SKUs (dynamic or static)*
- *Transport system (devices, equipment, conveyors, etc.)*
- *Control system (WMS, warehouse control system, and technologies – barcode scanner, pick by light, pick by voice, etc.).*

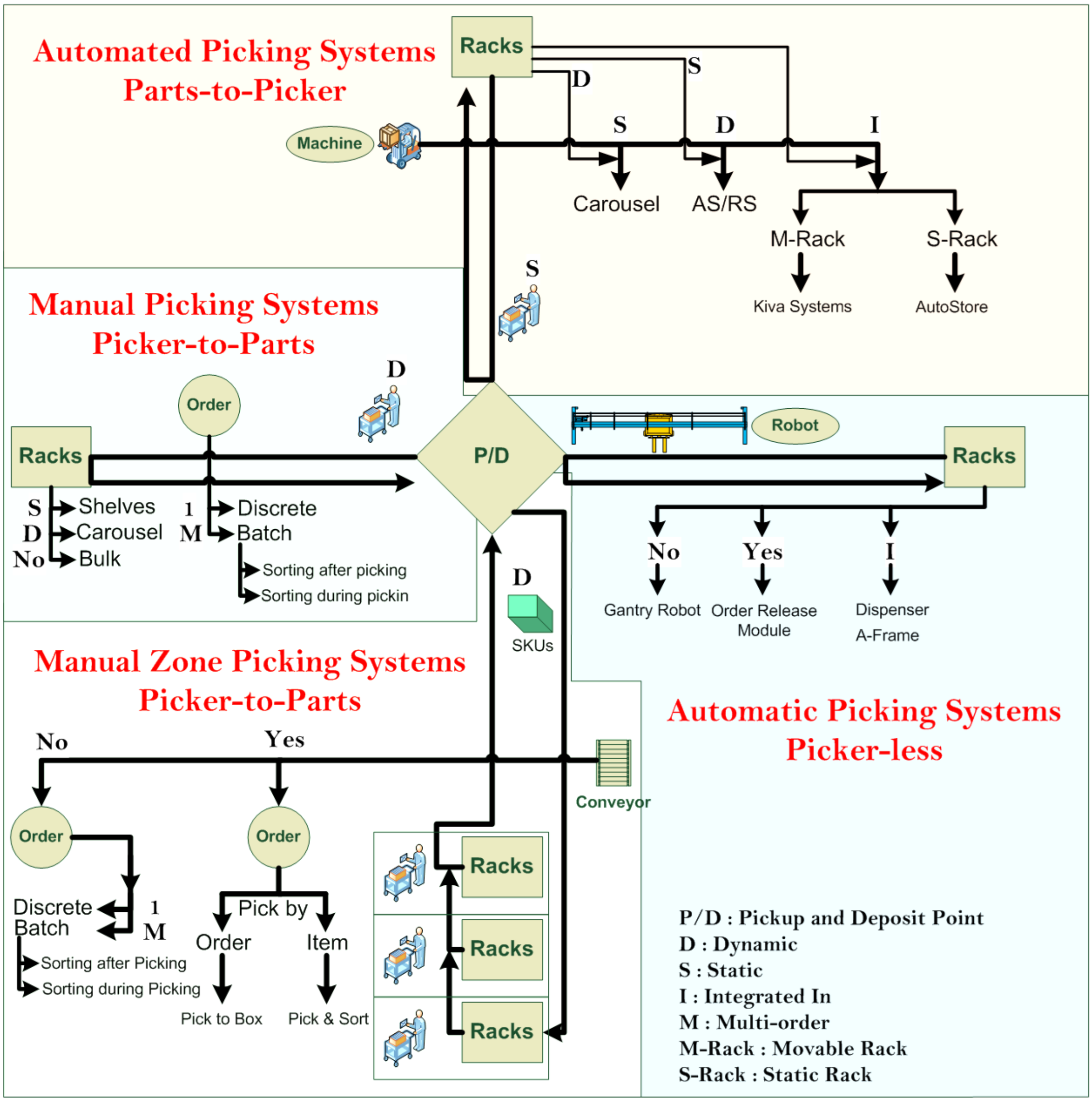


Figure 2.6 Classifications of OP and rack systems

P/D points (pick-station/dynamic or static): a dynamic point is a point that is movable. There may be many P/D points) in one OPS. As an example, in manual OPSs an OP trolley may be used (Dynamic Initial P/D Point). The picker picks the SKUs from the racks and deposits them on the trolley, then when the OPP is finished the SKUs are transported to the final P/D point, which may be the end packaging station. In semi-automated picking systems the picking process has two stages. The first stage is where the machine picks the SKUs from the racks and deposits them to the initial P/D point, these picked SKUs are transported to the picker (manual pick-station) to pick the required pieces and deposit them to the order containers (initial P/D point). These containers are then transported to the final P/D point. The final P/D points are usually static points, and the initial P/D point may be static or dynamic.

***Picker (human or machine/dynamic or static)*:** in manual OPS the picker is a human being. This picker uses dynamic behavior (moves to the storage location of the SKUs, then picks up the required items in a special sequence to satisfy the customer requests) in the system. This process is known as picker-to-parts. Sometimes the picker uses equipment such as a forklift or driverless vehicle to reach the storage locations of the required SKUs. Various technologies are used as identification systems, such as radio frequency identification (RFID) technology, barcode scanning technology, light technology and voice technology. In automated OPS the picker works at a static point (pick-station). The picked SKUs are automatically transported to this station by conveyors, machines or other automated mechanisms. This is known as parts-to-picker. In automatic OPS, there are no direct human efforts made in the picking process, but all processes are executed automatically by automated mechanisms. This is known as a picker-less system.

***Rack system (dynamic or static)*:** this classification depends on the behavior of the rack system. In a dynamic rack system, the rack moves itself to bring the required SKU to the pickup point, where the picker (human or machine) collects the SKU (full-case picking) or from the SKU (broken-case picking), as in carousel racking systems. A static rack system is a rack system, where there is no ability for the rack to change the storage locations of SKUs within it through its own movements, as in the shelf rack system. This can be done by using external efforts from humans or machines such as ASRS. An integrated rack system is a system where is some automated mechanisms are integrated with the rack system. There are two types of integrated system. Movable racks, such as those of the Kiva system, use a driverless vehicle or robot to bring the rack to the pick-station. The static rack includes a robot or automated mechanism built within the rack system (integrated in), as in AutoStore.

***SKUs (dynamic or static)*:** the system can be classified according to SKU behavior. A dynamic SKU is transported to a static picker (parts-to-picker). A dynamic picker moves to the static storage location of the SKU (picker-to-parts).

***Transport system (devices, equipment, conveyors, etc.)*:** classification can be according to the mechanical systems used. In the manual zone picking system, there are two different categories. One uses a conveyor between zones and the other does not use a conveyor. The OP strategies can be different according to the use of a conveyor.

***Control system (WMS, warehouse control system, technologies (barcode scanner, pick by light, pick by voice, etc.)*:** the system can be classified according to the technology which is used; in manual OPS light technology can be used to identify the required SKU location and the number of the required units, which is known as a pick by light system. Other systems use voice signals in order for the picker to identify the required SKUs and the required number.

2.2.5 Types of OP

Depending on the types of retrieval units, types of picks can be classified as pallet picks, case picks, or broken-case picks. Il-Choe and Sharp (1991) demonstrated a general structure for OPS, which had been presented previously as a working paper from the Material Handling Research Center at the Georgia Institute of Technology, by Yoon and Sharp (1996). According to this structure the OPSs can be divided into three types according to the size of the SKUs handled as follows

- *Pallet picking (partial or full)*
- *Case picking (full-case picking)*
- *Piece picking (broken-case picking or split-case picking)*

***Pallet picking system*:** when the picking quantity is a multiple of a full pallet load. This is a system designed to handle pallets as SKUs (unit-load warehouses). Usually all pallets are stored and retrieved with single pallet quantities. These types of warehouses can be found both upstream and downstream in the supply chain. This type of picking system can be found in the reserve area within warehouses. In the picker-to-parts system (manual picking system), forklifts and hand jacks, or other material handling equipment, is used. In the parts-to-picker system (automated system) automated storage and retrieval machines are usually used to store and to retrieve pallets automatically from a high-bay rack system. See Figure 2.7.

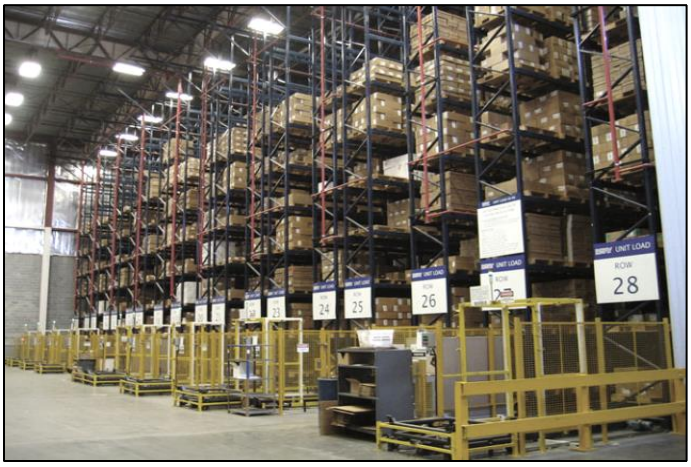


Figure 2.7 Parallel aisles of a pallet rack (Manzini, 2011)

Case picking (full-case picking)**:** when the picking quantity is a multiple of a case quantity but less than a full pallet load. The most suitable OP technology could be selected based on the DC Operating environment, the received product packaging form, and the picked products packaging way. As carrying cases the incoming pallets normally have only one SKU. A CPP is when one or more cases are retrieved from their storage location and stacked to form a new case, like a pallet. A manual CPS can involve a bulk storage area, where single SKUs are stored on pallets and a manual full-CPP using a pallet truck, as in Figure 2.8.

Figure 2.8 Example of a manual full-CPP (Bleifuß et al., 2012)

Piece picking (broken-case picking)**:** piece picking is also known as 'broken-case picking' or 'split-case picking' and involves an order pick, where the picking quantity is less than a full-case or is in pieces. In a split-CPS, individual items are picked from crates or open cartons, as in Figure 2.9. Normally broken-case picking includes a large number of item types, small quantities per pick, and short cycle times. Broken-CPPs are the most complicated, costly, and most effort-intensive types of OPS. Many technologies (pick by light, pick by voice, etc.) are used as identification systems to optimize this process. Several types of technologies can be combined to create an efficient picking system (automated or automatic).

Figure 2.9 Picking individual items from open cartons with a gravity flow rack (Manzini, 2011)

Today there is increasing demand to implement automated means of case picking, due to increased labor costs and increased pressure on operations to reduce the costs and the order cycle time. Many automated and automatic CPS can be found in the market today, such as mini-load storage and retrieval systems (mini-load AS/RS) and gantry robot CPS. Because of the great variation in required SKUs in CPP compared to the pallet (unit-load) picking process, case picking is more complex than the pallet picking process.

2.2.6 Classification of CPP

Recently the full-CPP has been the focus of much attention, especially with regard to minimizing operational costs and increasing distribution process efficiency in many DCs and industry sectors. Usually CPS has fixed, physical profile SKUs, familiar customers and stable demand. This depends on the types of products and businesses. CPP has great potential for automation from this perspective. There are thus many automated and automatic case picking systems on the market today. These systems can be divided into two kinds, as follows

- *Direct picking (the SKUs are the pallets)*
- *Indirect picking (the SKUs are the layers or cases)*

***Direct CPP*:** the incoming goods arrive as pallets; every pallet has only one type of product (article). These pallets are stored automatically in the high-bay rack system (AS/RS) or manually in a bulk storage system. The CPP can be executed directly from the pallet, automatically by using robots (such as gantry robot) or manually by a human picker, and it can be executed by splitting the pallet into cases and sorting the cases in the next stage according to the customer orders. At the end of the sorting, the system can be automated or a manual palletizing system.

***Indirect CPP*:** the incoming pallets of products are split into layers or cases and are stored in a buffering area such as a mini-load storage system, then the required cases are retrieved either automatically or manually in sequences according to the customer requests: see Figure 2.10.

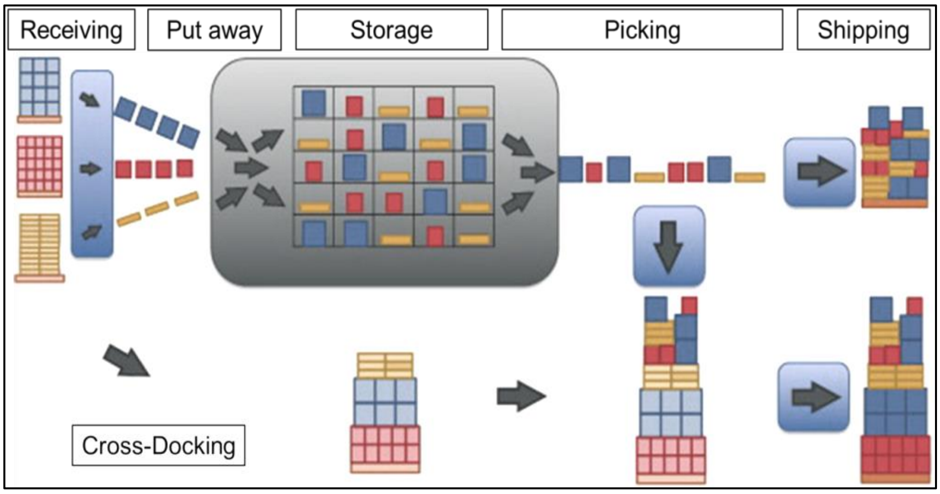


Figure 2.10 Material flows according to indirect CPP (Symbotic LLC 2014)

The investment costs in direct CPSs can be lower than those in the indirect system, but the operating costs are higher, due to the rise in required labor and the decrease in the throughput (pick rate). This can be changed according to the other OP design requirements.

2.3 Literature Review

Many companies have implemented the easiest route as the most accessible when selecting items based on customer order. Many of these activities entail the non-productive parts of the task. This represents wasted time as the order picker must travel along a horizontal line to pick the item, however, it is necessary to understand each method and piece of equipment in OPS. Industrial engineers should be responsible for maximizing OP activity with a large number of throughputs, as there are three methods that can be considered: piece picking, case picking and pallet picking operations. The piece picks deliver a large variety of products, but fewer SKUs can be retrieved compared to case picking. Case picking is an alternative for delivering a higher number of SKUs with high pick rates. Pick modules are especially designed to reorganize picking and for restocking product flow for case picking.

Case picking methods can be reviewed as discrete OP, batch picking, zone picking or wave picking. Many types of OP can be seen in a warehouse. Usually, multiple OP types cold be applied in a warehousing system. The principal difference between batch picking and discrete picking is that batch picking can be configured to obtain multiple orders simultaneously into one pick instruction. Discrete picking is based on fulfilling a single order, before the next new order is picked. The most common means of zoning are by using progressive assembly and parallel techniques (Parikh, 2006). Discrete OP is a basic and simple process, as a single worker walks to each section to collect all the items for a single order at a time. One picker starts to pick items from one order and then continues to select the next picked order. This system is common because of its simplicity and suitability for low volume item-picking. Eisenstein (2008) proposed an optimization method when designing discrete OP technologies based on two primary methods. The first is using high technology conveyor systems, and the second involves the excellent layout design of a warehouse. Batch picking can be described as a multi-OP, where the orders are batched together into one pick instruction. Batch picking minimizes the travel time of an order picker walking to the same locations. Only one order schedule is required in this picking system. Henn et al. (2012) noted that many solutions have been introduced for the order batching method. The most simple order batching algorithm is the ‘first come, first served’ batching rule, where multiple customer orders are picked simultaneously on one route. It is necessary to provide a sorting process in order to manage items according to a specific sequence.

Khachatryan (2006) conducted a research based on pick-to-buffer workstations using a “sort-while-pick” technique. The travel time from storage to the consolidation area can definitely be minimized. Zone picking can be configured as each order picker being assigned to a specific zone, where the pick area is divided into several pick zones. The order picker only has to pick and deliver the case directly into the order container, as it will be conveyed through all pick zones. Le-Duc (2005) conducted research to identify the optimal configuration of zones which minimizes the total completion time of batch picking. It is important to divide the picking area into zones that help to reach the goal of reducing time. Large companies are always in competition to meet customer expectations, and sometimes a batch picking is not more sustainable to support material flow. Wave picking is the most appropriate approach to handle more items and can be used to pick more orders. Wave picking can also be applied for various sizes and is convenient for a group of workers who need to complete the OP before moving to the next locations for the next wave.

2.3.1 OP efficiency improvement procedures

Several strategies and procedures can be executed to improve the OP efficiency. Many factors have effects on efficiency and can decide the best way to improve the efficiency and the effectiveness of the OPS. All factors which have an influence on the OP efficiency must be identified. According to Dekker et al. (2004) these factors may be:

- *Operating procedures (picking, routing, and storage)*
- *Changing product demand (demand fluctuation)*
- *Equipment (manual, automated, or automatic)*
- *Racking system of the warehouse (space utilizing)*
- *Layout of the warehouse (internal and external)*

***Operating procedures*:** could be the best solution to improve the efficiency of the OPP without a large investment in existing systems. According to existing research the operating policies that most improve the efficiency of the system are: picking, routing, and storage. Picker travel time in picker-to-part system represents 50% of the total OP time (Tompkins, 2010), and t, reducing traveling time is the best way to improve the efficiency of the OPP and the performance of the OPS. Picking policies can reduce the total traveling time by grouping two or more customer orders in one picking order (batch picking, zone picking and wave picking). Routing policies can reduce total traveling time by finding the best picking sequences and routes. Storage policies can reduce total traveling time by finding the best item storage locations in order to reduce the picker travel distances (Manzini, 2011).

***Changing product demand*:** the stability of customer demand has a significant effect on the design and cost of the OPS. In the reality, there is rarely stable customer demand within warehouses and DCs, and therefore the flexibility of the OPS is an important factor, and has a substantial influence on, and responsibility for, satisfying both customer and the distributor requirements.

***Equipment*:** refers to the automation level of the system. Whenever a system has a higher level of automation, it has lower operating costs, higher throughput and a lower order cycle time, but at the same time it has lower flexibility and a higher investment cost. The combination of these requirements could be produced a very good OPS. By virtue of new technologies and innovative ideas, many full-automated OPS have high flexibility and low investment costs

***Racking system of the warehouse*:** actually, the optimization of warehouse's capacity depends directly on the design of the racking system. A flexible racking system has more ability to deal with many different types and physical profiles of SKUs, and it has a vital role in item accessibility, which has effects on the system throughput and operating costs.

***Layout of the warehouse*:** the warehouse layout design problem has two issues (De Koster et al., 2007):

- *External layout design:* the best solution according to the identification and size of overall warehouse structure (location, sizing and its departments) related to the customers, type of goods, and transportation infrastructure.
- *Internal layout design:* the best solution according to intra-logistics requirements. Determining and sizing technical, structural and operational details for all parts of the system. Layout design has a significant effect on travel distance within the picking area. In low-level picker-to-part systems, aisle layout can optimize the travel distance by 60% (Caron et al., 2000).

2.3.2 Automated OPP

There is a set of circumstances today that makes it possible to deal with a lack of coordination resulting from a lack of efficiency inside the warehouse by discovering a region to enhance maximum support and to achieve a successful development. The warehouse industry is thus undergoing radical change in order to design and develop the automated picking system. An effective warehouse represents a set combination of automated technology to be carried out in daily operations. Warehouse automation is thus a common way to support increasing sales, especially for automated material handling system.

An automated warehouse can be configured as an inventory management system that contributes to a company with high and sustainable profitability (Hobkirk and O'Neill, 2007). Warehouse operators are still confirmed that the warehouse automation must be comprise the necessary equipment for a particular purpose with the operating technology (Baker and Halim, 2007). An automated warehouse is compact and involves the process flow of items from receiving area to the storage considering OP activities and transfers them to their assigned shipping door. Using the proper procedure based on a standard system design helps a project to finish right on time and make the process of investing money meet expectations. The foremost design to develop an automated warehouse is to automate with comprehensive process technology.

Many research organizations still have a long way in order to form an idea about technology based on automation. Over 40% of average industry respondents expend their money in the expectation of achieving a profit in the next 12 to 24 months based on automation (Wyland, 2008). Technology plays an extremely important role, especially in the warehouse, in order to make progress according to target and purpose. A billion dollars of money has been spent every year on automated warehouse (Gilmore and Holste, 2009). There are many companies who desire to improve the performance of warehousing with automated systems (Wang et al., 2010). Many warehouses and DCs are starting in determining and discovering the problems in their OPPs to eliminate blockage or a point of congestion inside the warehouse in order to make the performance become more effective.

During the order process, retailers are forced to tighten the control and setting up delivery schedules, so as to prevent stock out situation. An order picker has to travel to numerous storage locations to completely pick up each order. This can also lead to the problem that much labor is required, including to decide what item has to be picked and the location of the item. Using full-case picking involving new technologies could minimize travel time. The up-front cost of this solution is based on the level of automation selected. Automated full-case picking represents a combination of process and supporting technologies. Full-case picking can be classified into two categories, discrete OP or batch picking.

Batch picking is the best solution to minimize travel time. De Koster et al. (2007) have defined batch picking as a solution that places a set of orders into a number of subsets, which can be retrieved by a single picking tour. Batch picking is a common way to fulfill multiple orders at a time in order to push the boundaries of the feasibility of material handling systems. In the past few years, full-case picking has been presented as interesting and important in order to reduce the costs of the warehouses and DCs. Andriansyah (2011), Caputo and Pelagagge (2006) and Li and Bozer (2010) have discussed solutions based on fully automated picking technologies. These solutions have many benefits, and particularly contribute to a solid ROI, reduce the cost and increase the throughput (Gilmore and Holste, 2009). New innovations in automated full-case picking, which provide much momentum, are currently being introduced.

2.3.3 Case picking automation

Many companies are looking to the future and have great enthusiasm the newer technology of ACP. Picking is perceived as the most labor-intensive task in the warehouse, and management should always take responsibility to select the most efficient picking solution. An ACP can be defined as a set of comprehensive technologies that are used to automate traditional case picking, which continue to gain advantages by lowering dependency on the availability of human power, improving service levels, minimizing OP time and using less floor space. By tailoring each system depending on their requirements, automated picking systems can make great achievements. Automated warehouses provide a huge benefit, as many companies look forward to designing and developing new automated warehouse. Automated warehouses contribute to increasing service consistency, speed of service, throughput, and flexibility as well as reducing labor costs (Baker and Halim, 2007). Gilmore and Holste (2009) summarize the drivers of case picking automation requirements, as in Figure 2.11.

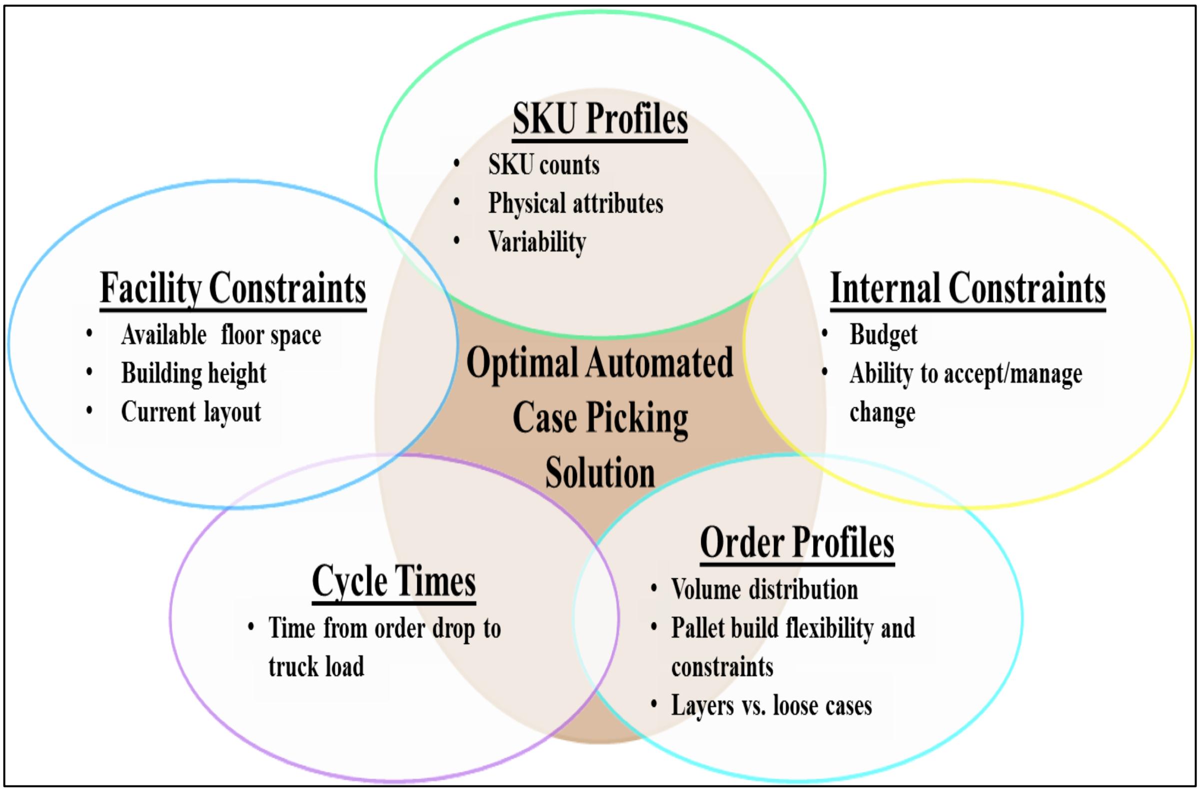


Figure 2.11 Drivers of case picking automation requirements (Gilmore and Holste, 2009)

Many ACP solutions can be found related to the characteristics of different industry sectors and the variety of distribution operating models within warehouses and DCs. Characteristics of SKUs and orders, cycle time requirements, facility constraints, and other factors (budgets, appetite for risk, and the level of operational change that can be added) have a strong influence on selecting or designing the optimal ACP solution for the company.

2.3.4 Basic justifications for automation

Full-case picking is an interesting alternative for reducing cost, and increasing throughput and quality in automated warehouses, and therefore a review of automating full-CPSs has been conducted. In order for the automated picking process in the warehouse to be performed more efficiently, it should be noted that an optimal control approach and great design are necessary. A lack of innovation in automated materials handling systems can be a major issue in DCs.

Automation has grown rapidly with the increased delivery of mixed items, the need for extensive unit items, and random item orientation in different locations, however, high intensity manual work affects both the overall logistic cost and the provision of service to customers. There is growing interest in scale efficiency that can help the centralized inventories in companies to improve both productivity and lead times. Many research programs have been conducted to determine the most convenient systems for automated warehouses. Investment in automated solutions also involves many companies concerned about turnover, productivity and also the significance of revenues. Many companies need to redesign their warehouse systems, as internal pressure has pushed for automation to be used in picking systems. In other words their intention is to improve efficiency and lower the cost.

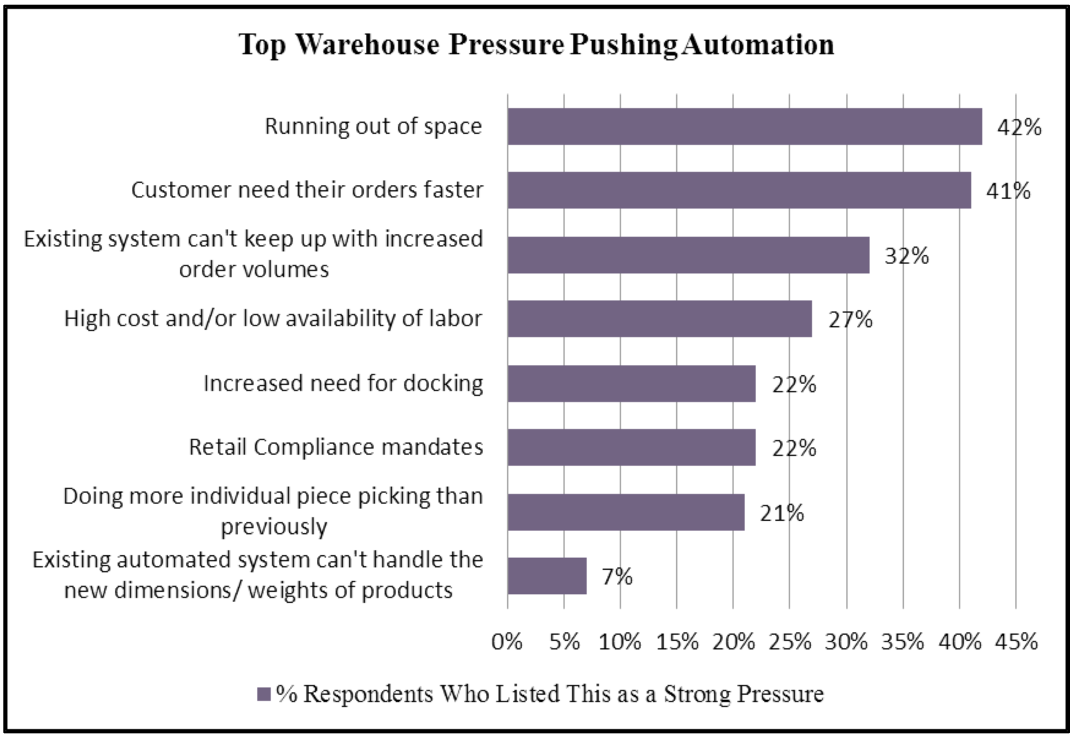


Figure 2.12 Justifications of OP automation (Hobkirk and O'Neill, 2007)

Benchmarking research helps to quickly acquire knowledge, information and a practical understanding of the mutual relationship between the utilization rate of the automated warehouse and their performance, as well their exhaustive effect. According to the survey results reported by Hobkirk and O'Neill (2007), requirement space and rapidly receiving orders, are the top pressures on warehouses nowadays, with about 42% and 41% of the companies considering both as highly pressured. While, the high cost and the low availability of labor indicates by 27% of respondents' opinion and only 7% of respondents' opinion refers to the point of existing automated system cannot handle the new dimension/weights of product respondents. It can be concluded that rapid delivery orders and space concerns must be taken seriously by companies, so that the design and improvement of warehouse can contribute according to expectations.

Several different functional areas ought to be borne in mind during the OPS designing process. Sometimes many OPSs work together in an integrated system to satisfy the customer orders, OP types, and strategies. Technologies with integrated equipment, controlling systems, and WMS could be unified into one system. Different tasks are assigned in order to separate functional areas, and the appropriate equipment and control strategies are specified for each area. Things that a manager needs to consider when specifying or designing an OPS are: demand, items order, wave length, maximum orders/manual pack station, labor cost/picker, labor cost/packer, interest rate, years of service, picking standard (manual), packing standard (manual), annualized cost/pack station (manual), picking standard (automated), packing standard (automated), annualized cost/pack stated (automated), conveyor speed, nominal induction rate, labor cost/inductor, annualized fixed cost of sorter, annualized cost/induction station (Webster et al., 2014).

The difficulties of projects are indicated by a large number of testing and commissioning issues. IT systems have always been a major problem, followed by the processes of installing automated equipment, building construction, people factors and the complexity involved in amalgamating a number of sites (Baker and Hamil, 2007). The huge number of steps in automation projects describes the complex preconditions of such projects, but in spite of this the process has developed gradually to achieve success while retaining control for some period of time within budget. Automation needs a long term sustainability plan in order to meet future needs. Recently, the OPP became more complex, therefore the multiple order process has become important in warehouses and DCs. Multiple order process has been discussed by Khojasteh-Ghamari and Son (2008), Andriansyah (2011) and also Wang et al. (2010) in order to optimize the OPP based on deliver a large number of items simultaneously from the storage area.

Fumi et al. (2013) have discussed this based on minimizing warehouse space with a dedicated storage policy. Lerher et al. (2013) have developed a method to minimize cost and increase quality. Roodbergen and Vis (2009) discussed the literature concerning the impact of the new AS/RS design that operates under computerized control in both production and distribution environments. Khachatryan (2006) reviewed the research on how to develop a system that facilitates a progressive consolidation of customer orders without any sorting system downstream, specifically for high volume small parts OPS. Lerher et al. (2007) discussed a small improvement to support full automation in the warehouse, which is bleeding edge technology that is too expensive and inflexible.

Design methodology is a crucial element that must be considered when choosing optimal variants in order to minimize average total cost, however, over-investment has been identified as a problem and requires clarity of future demand in picking automation, which indicates a major weakness in the business model. Extensive information technology changes have also become a critical part of warehouse automation projects, dramatically changing the business landscape. A lack of flexibility in automation is a major concern and thus needs to be considered during planning and implementing scenarios. There is a limitation in terms of space and capacity when fulfilling customer orders. In addition to labor and employment issues, there is an economic problem present in warehousing system nowadays, where every warehouse manager is looking to reduce operating costs, and develop better performance to meet customer expectations.

2.3.5 Limitations, problems and risks of automation

It is appropriate to consider a staffing issue that requires a change in the workplace, as regards the new automation technology that has been introduced. Implementing new technology and systems can be frightening for many companies, coupled with a fear that the technology may not work properly. The high capital investments involved are also risky as they require a large amount of up-front cost and involve a lack of flexibility. A great many companies have no interest in making an investment in automated handling systems. A survey and review of approaches was conducted with 210 managers and executives, about case picking automation. All respondents were from a wide variety of different industries mostly consumer goods, food and beverage companies and also retailers. There are many barriers that must be considered in order to perform ACP, especially in the next generation. According to the survey results of Gilmore and Holste (2009), a lack of ROI was seen as a major concern by most companies, with 73% of respondents indicating that it is the most important issue. Some respondents were interested in the potential of new automated picking solutions, but do not have enough knowledge regarding the amount of investment, and 47% of respondents were concerned that they did not have enough information to evaluate the total amount of investment required. 19% of respondents were concerned that the automated picking system may not work as expected, and 14% of the respondents were unwilling to invest in an automated picking system. 11% of respondents were concerned about staff performance, as new technologies often create a need for new rules, and 16% of respondents indicated other factors such as problems regarding flexibility over time and the reliability of the system (see Figure 2.13).

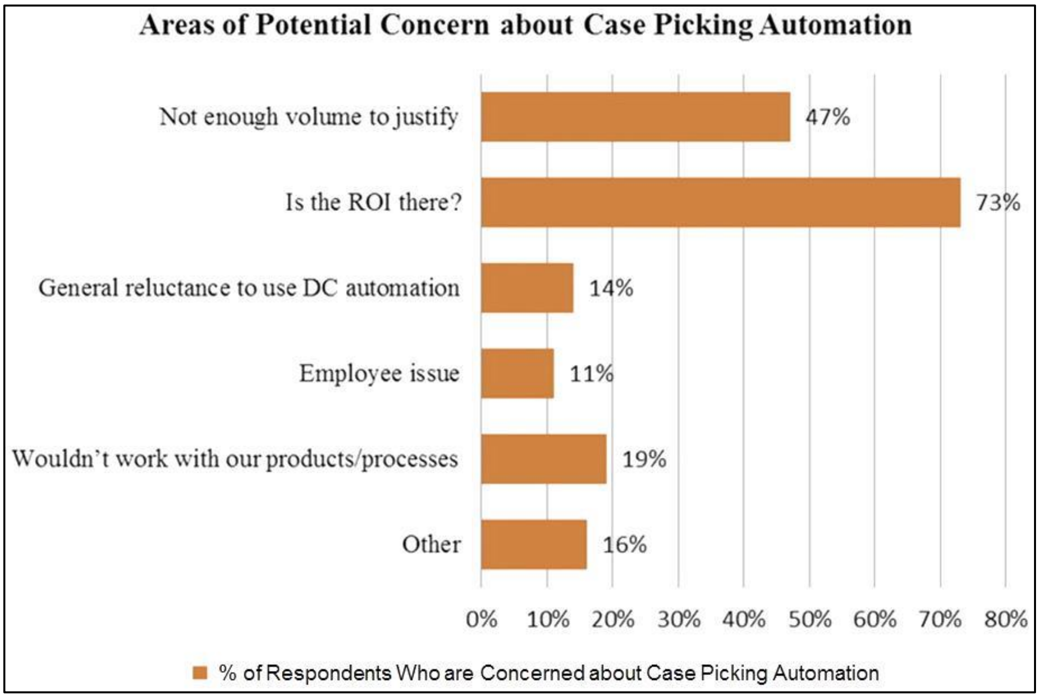


Figure 2.13 Limitations, problems, and risks of automation (Gilmore and Holste, 2009)

Many DCs are simply not set up to handle a higher number of orders by customer. Inadvertent patent infringement must be considered, especially for companies that are going to design and develop new solutions regarding the automation picking system (Mekhaya, 2000). There are still companies that would be interested in an automated picking system with better throughput and reducing costs, but currently there is no proper solution to this.

2.3.6 Basic design requirements and stages of an OPS

There are many ways in which research has been conducted regarding designing an effective full-CPS. The warehouse design stage is the most important part of the process, and requires an effective concept in order to solve the problems and to find the best method. Many decisions with possible consequences must be made at an early design stage. First, it is necessary to identify the overall warehouse structure; secondly, selecting the dimensions and sizing the warehouse. A detailed design layout must be configured and should determine the basic needs of warehouse equipment. Finally, the best operating strategy to generate value must be defined. Yoon and Sharp (1996) proposed three OPS design stages:

- *Input stage* (determining all managerial considerations, operational constraints, and transaction data to determine the overall OPS structure)
- *Selection stage* (determining the physical and technical required features, and operating policies of all subsystems)
- *Evaluation stage* (determining and selecting the quantitative and qualitative characteristics of all subsystems).

Dallari et al. (2009) later added a new stage: *Detail stage* (trying to optimize all subsystem characteristics in order to optimize overall system performance, see Figure 2.14).

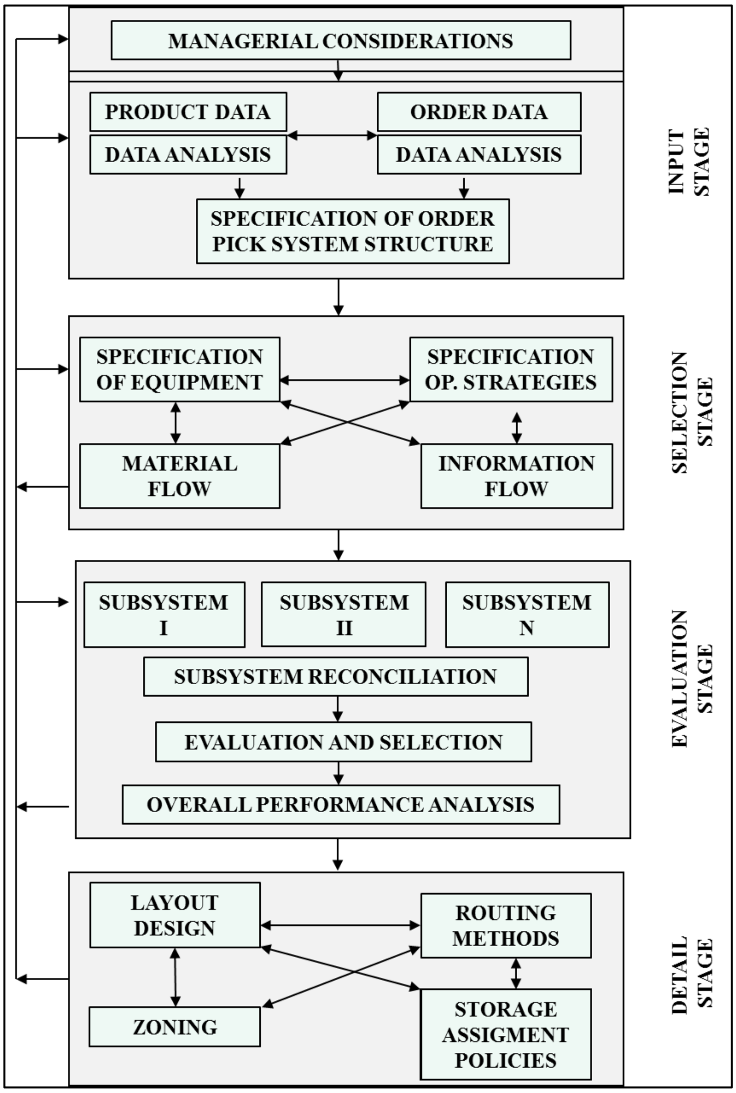


Figure 2.14 OPS design methodology (Dallari et al., 2009)

De Koster et al. (2007) have proposed five main operational policies during the design stage: *routing*, *storage*, *batching*, *zoning* and *order release mode*. Gu et al. (2010) suggested that operational performance measured in the early design stage should be taken into account. It is almost impossible to change a design decision quickly when the warehouse has already been created. Bartholdi III and Hackman (2010) have clearly explained a statistical approach to estimate the amount of throughput as an early step in designing an automated picking system before performing a simulation. Khachatryan (2006) suggested that the most crucial support decisions in the very preliminary stages of design involve investigating an analytical model of picking systems. Gu et al. (2010) defined the main criteria in the early stages, which the designer of the automated warehouse should define: warehouse structure, determining an overall detailed layout of warehouse, making a good selection of warehouse equipment, and finding an effective operational strategy.

Baker and Halim (2007) suggested that a first step is to determine the current level of support for flexibility issues, and Roodbergen and Vis (2009) suggested that physical layout must be designed correctly because of its relative permanence and inflexibility. Data analysis is important to set up the capacity of a warehouse based on levels of automation. Both external and internal layouts must be developed. The selection of material handling equipment must also be made, such as which different manipulators are used. A cost consideration is then calculated, including land costs, building costs, equipment costs, storage rack facility costs, labor costs and maintenance costs.

The most important steps of any warehouse design are thus to develop an optimization model and heuristic algorithm in order to determine the locations of SKUs in different storage areas. Secondly, evaluate the lane depths for different products to determine the best storage space utilization rate. The aisle structure of a storage warehouse must then be determined, to reduce material handling costs. Material handling systems must be selected based on the level of automation in a warehouse, however, Gu et al. (2010) proposed that in practice, this selection should be much better made according to the personal experience of designers and managers.

Marin and Carrasco-Gallego (2013) also proposed an OPS designing method, where the method used depends on two references: the first is based on the authors' professional experience in a real case designing an automatic warehouse, and the second is based on an overview of scientific papers. The combination has created the best approach to developing flexibility in warehouse design. The conditions of storage policy must then be clarified for better results regarding capacity and travel time. There are three main criteria that should always be emphasized when designing a warehouse: development of procedure, type of systems and also organizational policies. The relationships between products, system and process are crucial in designing a warehouse.

2.3.7 Automated full-CPSs

This section discusses different convenient methods for high volume, automated full-case picking in the distribution, storage and retrieval process. Today, many companies face a high level of competition in supply chain services and the automated material handling market, therefore, a lot of innovations have been developed in order to raising the competition level and improving the efficiency of the OPSs. A system that moves, stores and retrieves a high volume of full-case picking rapidly, using less space, is the best approach to an automated picking system.

The methods of automation currently available on the market are clearly out of the ordinary and can be appreciated. This literature review focuses on full-case picking operations as well as the many innovative methods that support the automation of this system. De Koster et al. (2007) suggested that automated OP involves the process of automatically storing and retrieving customer orders, conveying the orders to assigned locations, and packing and handling the orders.

There are three main stages in warehousing system. The first stage is the receiving stage for the incoming pallets of the products, which may be coming directly from production or from other suppliers to the warehouse. The second stage is the storage stage (put-away) for the received products, which may be in a high-bay warehousing system or in other type of warehousing system. The third stage is the extraction and retrieval stage, where the customer’s required products are retrieved in a special sequence, are aggregated for building a transport unit (mix pallets or rainbow pallets), and transported from the picking area to the assigned shipping door.

The pallet transfer solution is clearly explained as a set of sequential operations created in a factory whereby the products at the end, generally a pallet, must be wrapped using highly stretchable plastic film. Usually automated pallet stretch wrapping is used. An efficient process will then be carried out to label the pallets and they will be transported rapidly to the storage warehouse. ASRS has come to mean a single system, where the output pallets of finished goods must be transferred into the storage warehouse as quickly as possible, and at the same time must also be retrieved as efficiently as possible from the storage warehouse according to the order made by the customer. ASRSs consist of a variety of computer controlled systems, which are designed to store and retrieve items automatically in the warehouse and DCs. In order to support pallet shipping and sorting systems there are many alternatives that can be used to sort pallets at the end of the shipping dock and to load outbound trailers automatically. It is interesting to consider both mechanized and fully automated systems in this literature review.

Pick-to-Belt

Pick-to-belt, with a downstream sorting system, is the most widely method used in the materials handling industry. Generally a picker has to move to the location on one occasion, and picks all the cases, according to the order, and places them on a conveyor. Gilmore and Holste (2009) present literature showing that all the information about case picking is directed by a WMS. The cases that are needed for the order are conveyed out from the pick area and onto the sorting conveyor. Sorting systems are used to separate picked products based on order, customer and shipping destination. Andriansyah (2011) has applied this method at workstations, where the operator is required to check whether the items crate has become empty. The empty item crate is placed onto a takeaway conveyor. An order picker at the workstation picks all the items from a single order, which is full-case picking.

Khachatryan (2006) has conducted also research with respect to this method. Two categories of the pick zone were studied, pick-to-buffer zone workstations and pick-to-container zone workstations, which require order pickers to move along the pick area, pick items and put them into the order container. Pick-to-buffer workstations involve using the "sort-while-pick" technique, because the content area of the pick buffer is assigned only for a single order and items are automatically then transferred into the right order containers. These order containers are conveyed through all pick zones before the assembly process.

Order pickers can be classified into two categories, manual or robotic, that are used to place items into pick buffers and not directly into the order container. Travel metrics and the capacity of an order are considered to make a decision about which category is used. Note that there are three types of travel metric within these studies, *Euclidean* (the Euclidean distance is the straight line distance between two points), *Rectilinear* (the Rectilinear distance is the distance between two points measured along axes at right angles) and *Chebyshev* (the Chebyshev distance is the maximum distance in either coordinate direction). Khachatryan (2006) explained that the only approach for robotic order pickers is by applying the Chebyshev distance. This is because the robots have two independent motors that move in both horizontal and vertical directions. Reddy (2014) built an autonomous robot that could be used to detect moving objects on conveyor belts by using color sensors based on certain criteria. This autonomous robot transfers the moving object to a specific location and significantly reduces the human job of walking across the warehouse all day.

Pick-to-container is executed in a zone picking workstation in which items can be easily stored and retrieved. Order containers are then conveyed to all pick zones and temporary stops in the pick-station, meanwhile order picker will start to pick items and put them directly into the order containers in response to a specific order. Picking and the assembly process occurs simultaneously. There is another alternative, where the operator only moves to the put-away location of the items to be replenished and starts reloading the appropriate items in the flow racks side by side, which form an A-shaped frame. Caputo and Pelagagge (2006) introduced the A-Frame dispenser and Bartholdi III and Hackman (2010), in their book ‘Warehouse and Distribution Science’ explained that it serves as an automated picking technology.

An A-Frame is an automated picking or dispensing machine that tends to be used in actual DC by dropping items onto a conveyor. Typically, this system straddles a conveyor, where a picking process for small-part high-volume products is required. This system is largely used for cosmetic or pharmaceutical products. An A-Frame does not require labor as the items are deposited automatically into a box that will be conveyed to another location. Restocking the products can be done without interrupting the process of picking itself. The system is only used for single orders, where items are automatically released from the frame and conveyed to the collection workstation. They are then transferred into order containers. This method is well proven to be able to scale down the required amount of manpower and also allow changes to volumes, however, many companies are more interested in, and looking forward to ACP without human intervention. A-frame dispensers can be configured as flexible OPs since they are applicable to various situations. The total labor cost could also be reduced.

AGV and Laser Guided Vehicles (LGV)

Schulze et al. (2008) have conducted research into the development of an AGV system as an important part in the material handling system for a new generation of systems that have come onto the market. This system is more flexible and suitable for use in DCs. Gilmore and Holste (2009) have explained that AGVs can be divided into two categories, product-to-picker systems and picker-to-product systems. The main concept of product-to-picker is where the AGV sends full pallets to the workstations. Order pickers are placed at each workstation and the case picking is carried out. After the picks are complete, the AGV moves to another workstation or moves back to a stationary position. The main concept of picker-to-product systems, is that the AGV moves automatically down the aisle and the picker picks all the cases according to the order, to put them on the robot’s pallet. The AGV are directed all the way through a variety of pick locations by a WMS. This will be navigated according to an optimal path dictated by the robot control, so that it will reach precisely the required pick position at a picking zone.

Butdee et al. (2008) developed an algorithm based on memorizing the path and kinematics determination of the movement, where the vehicle is mounted by an inboard programmable logic controller (PLC). Human intervention and physical guides are not necessary. This method saves travel time in particular, as the vehicle can move along the path to specific locations, and also increases productivity. Sharma (2012) presented a classification scheme for the AGV system in order to identify the most relevant AGV design for certain criteria. This scheme helps designer have a better understanding of the impact of design decisions on controller functionality.

Lerher et al. (2013) have explained that most of the conventional warehousing systems utilize AGV technology with automated forklift trucks, and are directed by warehousing management systems. This technology is developed with wire that has been embedded in the floor and creates an electromagnetic field. Activated sensors are equipped to make sure the forklifts move on the right paths. According to white papers compiled by MWPVL (2011), in 2006 the *Kollmorgen Corporation* developed a driverless forklift that supports full-case picking, where the order picker does not have to get on and off the truck. The driverless truck continues to automatically deliver the pallets to assigned locations. In 2003 the Seegrid Corporation designed a vision guided vehicle that moves without wires, tapes or lasers. This technology drives the machine to start and stop only at necessary pick locations.

Kollmorgen and *Seegrid* have designed two different methods that support driverless trucks, and both methods are appropriate for full-CPP. Anderson (2013) conducted a study into laser navigation systems for automatic guided vehicles. LGV is an advanced technology, which allows the application of wireless navigation through reflective tape on walls. The top of the LGV is equipped with a laser beam which triangulates its position using reflective tape on walls. The system continually traces and measures a series of triangles to determine the distances and calculate its relative position, then, it will automatically compare its actual position to its calculated position. This technology is quite expensive, however, especially the cost of equipment and it is also slow, so the technology is not suitable for fast-moving goods. The LGV method also has the ability to transfer pallets from the storage warehouse to the receiving shipping dock area.

Today, some LGVs have been equipped with sonar technology that is capable of navigating and detecting objects. This technology can also be used for trailer loading functions. Dematic and Crown Equipment Corporation companies have presented laser truck technology that contributes to a high volume of throughput. The Crown Equipment Corporation Company has developed the *QuickPick* Remote Advance, based on a wireless transceiver glove. A laser signal will be delivered directly to the pallet jack when the operator pushes a button on the glove. This laser technology is efficient as it can detect any obstacles in front of the truck and will stop immediately. It is easy to navigate and requires no sorting, however, this method still requires manual picking and human intervention.

Leber and Wulfraat (2013) have discussed the new picking system *AutoStore*, which involves automated access of goods to the person picking the unbundled solution. In a white paper compiled by MWPVL (2012), a comprehensive, in-depth overview of *AutoStore* is presented. On receiving, the products are placed into standardized crates that are conveyed to induction points in the *AutoStore* system. Robotic mobile vehicles move on an XY axis on top of 17 high storage buffers consisting of vertical stacks of bins. Robots automatically retrieve crates from the vertical stacks for presentation at picking work stations. The operator picks required SKU/quantity and the crate with residual inventory is returned to the top of the cube to be stored in a vertical stack. *AutoStore* robots are equipped with a hoist that uses four rolled up steel bands that reach into a stack to pull out the bins. It is ideal for environments where a large variety of slow moving parts require high density storage to minimize warehouse space requirements.

Conveyor Based Automated Picking System

Today, many companies use the principle of a belt conveyor, but in more advanced to support the CPP. This conveyor-based automated picking system can be divided into two categories, horizontally oriented systems and vertically oriented systems. Hobkirk and O’Neill (2007) have explained that conveyor based picking is used to transport the order container from the picking zone until the final function of consolidation. The horizontal order release system with ACP became popular in the 1970s. Increasing concerns related to operational issues such as increasing demand enclose with replenishment and fulfillment as well as increasing product damage meant that many companies did not develop an interest in this method. The concept is basically that when the process of de-palletizing is complete, the case is conveyed directly to the sorter area, which is behind the full-case SKU lines. There, the cases are transported to the appropriate SKU position. Normally the system uses a combination of gravity and drive motors to move the cases forward to the opposite end. The conveyors are the heart of this OPS, and indispensable in order to bring all the items to their assigned locations. The gravity roller conveyors could be used because of their comprehensibility and consider the following cost savings. In order to ensure the cases are carried out appropriately according to the ideal SKU sequence, picked cases are delivered one at a time from the lane. The released case will be conveyed to an outbound sorter and will be transported based on specific orders.

Andriansyah (2011) has developed a corresponding method using a closed-loop conveyor in which mini-loads are located far from the workstations. There are various types of end-of-aisle OPS. Within this research, a mini-load with a closed-loop conveyor is used as a solution to fulfill multiple orders at a time. This closed-loop conveyor works with an order picker at the workstation picking the items according to one order, which serves as full-case picking. Multiple storage racks separated from workstations mean that items for multiple orders can be retrieved simultaneously, and permit more SKUs to be stored. In other words, this research has been conducted on end-of-aisle OPS, which comprises a mini-load, located far from the workstation for picking activity, and also a closed-loop conveyor, however, it requires a relatively large space.

Bleifuß et al. (2012) also used a similar method based on collecting incoming pallets dispatched by suppliers. The incoming pallets deliver different layers of cases of a single SKU, called rainbow pallets, with one SKU per layer. These trays are then delivered to the storage area in the warehouse. The location of each tray in the warehouse is organized through the Schaefer Tray System (STS). In order to retrieve the items from the storage area, ACP is performed by delivering one or more cases from the tray onto an intermediate buffer. The cases are then transported into collecting conveyor belts. Finally, the cases are transported to an automatic palletizer and a wrapping and labeling process takes place before the cases are sent for shipping.

Wang et al. (2010) introduced a framework based on the RFID principle conveyor solution, serving as an application of new technology. They proposed using RFID tags and wireless communication network to support the automation of large numbers of customizable items. Items can be placed at any location in the storage area, and a similar type of each item can be located in more than one location. RFID still requires manual intervention to drive and trace warehouse activities.

Nazzal et al. (2008) presented an analytical model to evaluate the system stability and also to precisely estimate the work in process on conveyors. A horizontal pallet transfer system is the most commonly used and well established production facility, because this system has been around the longest. There are many recent technologies available for automated solutions in order to support distribution operations. According to white papers compiled by MWPVL (2013), an air chain pallet accumulation conveyor will be used in support of a long horizontal transfer to moderate the impact, a strand chain conveyor is used to support a smooth continuous transfer, a live chain driven roller conveyor is used to support maximal flexibility, mechanical right angle transfer units are the best approach to transporting pallets 90 degrees at the point of intersection, and rotating conveyor turntables can be used to change the relative position of a pallet.

The vertical order release system can be viewed as an automatic machine which is designed to release a specific amount of something. This system thus has the ability to automatically pick and release cases onto the takeaway conveyor travel path at the downstream station. The general idea is that the top of the machine is filled with products and at the bottom of the machine is the place where the products will be released according to specific orders from the customer. The main concept is that the pick machine is made up of a series of short flippers which pivot trays can raise and lower to receive and send out the cases, as presented in the literature by Gilmore and Holste (2009). The benefits of using this method is that it is reliable and automatic case picking, however, it might not be appropriate for fragile products. According to MWPVL (2013), the vertical order release system solution is the most common way to transfer stretch wrapped pallets from production to a storage warehouse that occupies mezzanine structures. This system is more beneficial in providing enough space to transfer empty pallets, raw materials and packaging supplies during the production process. This area also needs to be kept free for a fire escape floor plan. Typically, the working principle of this system is that a pallet conveyor will provide pallets to the vertical lift elevators and then all these pallets will be elevated to a mezzanine one at a time. Crum (2011) designed and fabricated a vertical reciprocating conveyor to deal with complaints made by the operators. This system is used to transfer all the items to and from a mezzanine.

Carousel

A carousel is a rotating platform consisting of a number of shelves that have been used in an ASRS. An order picker stands in a fixed position without traveling to a case pick area, and the storage location moves to the order picker. This is interesting because the carousel moves in a circle and the picker has time to do another task or perhaps serve another carousel, however, as more than one randomly picked product from the carousel is served, then, the same worker must take it into account to make sure item replenishment is complete. Usually, a picker works at a pod, or there may be more carousels supported by sorting conveyor systems which are large and very complicated. For every single customer order, it is crucial to find the shortest possible route to minimize travel time, but when an order is relatively large, then a picker has to visit many locations on the carousel. In order to connect the sequence of the order, however, it is better to define the fastest way to pick an order from one pick location to the next pick location. There are only two possibilities: when the last pick location is after a clockwise rotation, then the next pick location will be in a counter-clockwise rotation, however, if the last pick location is in a counter-clockwise rotation, then, the next pick location will be clockwise rotation. Park et al. (2003) derived expressions for the throughput and the picker utilization rate of a carousel in order to evaluate the most appropriate model for both robot and human pickers.

Meller and Klote (2004) developed an analytical model to evaluate the throughput of pods of carousels when human pickers are used. This multiple carousel system can deliver a higher number of throughputs at the same time. Litvak and Vlasiou (2010) have examined the improvements of the standard carousels into the multiple carousel system. They used this system to solve a problem in order to balance between order picker utilization rates and their response times. Wang et al. (2013) presented research concerning a material handling system with a multiple carousel system and one picker. The carousel was a closed-loop rotatable storage system, where there are a large number of different items stored on shelves. They developed a solution to minimize the total OP time and give an optimal pick sequence. The carousel is highly versatile because the items rotate to the order picker, where it is possible to rotate in a horizontal or vertical direction. The order picker does not have to walk down the aisle to pick the items, because carousels can be built side by side and therefore improve the maximum space utilization rate. It becomes necessary to pick and restock the items more regularly, which can cause many problems, particularly lowering the rate of picking and the ability of an operation to perform and produce which may fail to respond to surges in demand. Horizontal carousels are often used to improve storage density in operations and reduce the total work hours. A lack of coordination between the carousel and the order picker will reduce the average expected throughput since the order picker is busy and cannot serve another carousel simultaneously.

Gantry Robot

A gantry robot functions to catch, deliver and arrange cases on the warehouse floor, in the close packed and very dense storage which creates an active inventory location. The main concept is that the gantry robot quickly chooses one or perhaps multiple cases from the active area and transports them onto the takeaway conveyor travel path. The cases can be selected and transported according to the appropriate pallet sequence by using control system software. This method is flexible, requires a relatively small footprint, and most importantly is a full-ACP, however, it may not work properly with weak bottom cases.

Khachatryan (2006) confirmed that gantry robots are not the major contributor to the whole system. This is because in automatic systems, both throughput and service level must be according to the specific system design parameters, and therefore, it is much better to consider the whole part of parameters as a package of automatic picking system. The picker's travel time approximation was modeled relying on item buffers and order buffers. Item buffer technology, with the robotic order picker type and spread layout of item movement, is traced via the system. Ata et al. (2009) designed and developed a gantry robot to automate storage and retrieval systems. They designed a gripper tool for robotic picking to pick items into accurate boxes using a light sensor. A combination of robotic gantries, the conveyor system and intelligent software is an alternative way to automatically pick full-cases.

Generally, four main stages are considered in this specific ACP solution. During the receiving and de-palletizing stages, the robot transfers whole layers from the pallet onto an unscrambling conveyor, where sorting activities take place. In the second stage, pick robots pick the cases that have been separated and bring them into an active inventory zone. There, the pick robots stack the cases on the floor: this is the third stage. In the last stage, the pick robots feed the stack cases onto the conveyor and turn the cases to convey the cases directly to the assigned shipping door.

Li and Masood (2008) presented a methodology and research approach to modelling a high speed palletizing process involving two robots, based on queuing theory. They have concerns about the dynamic properties, especially whether they are effective in meeting the two main criteria, utilization rate and congestion requirements. Generally, gantry robots and work performance is based on the behavior of the material flow. Talpur and Shaikh (2012) have used this automation of mobile pick and place robotic system for the small food industry. The system contributed to minimizing the cost and to eliminating manual tasks. Computer hardware and software are required to design this complex system, for strong integration.

They have also created a flexible gripper design to pick and place items efficiently. The combination of robotic gantries, conveyor system and intelligent software could deliver benefits such as eliminating bottlenecks for process improvements, increasing accuracy, providing precise information, reducing product loss, maximizing space utilization rate, and most importantly eliminating manual OP.

Honkanen and Miikkulainen (2014) from the *CimCorp* company received a patent for the idea of a gantry robot picking system, where an overhead robot system picks up, moves and delivers objects in a warehouse area, such as boxes, vehicle tires and other stackable objects. These gantry robots (known as 'multipicks') are built with a stationary steel frame, a moving bridge and a moving carriage. The mechanisms, which function similarly to a crane, operate near the ceiling and reach down to pick and stack orders. Attached to the gantry robot is a gripper for holding and releasing products. The gripper can hold loaded pallets, layers of product, small groups or individually selected cases, cartons, bundles, kegs, consumer products, snack food, tires and more.

ASRS as CPS

ASRS consists of a variety of computer-controlled systems, which are designed to store and retrieve items automatically in a warehouse or a DC. This technology was first developed in the 1960s. An ASRS is fully automated system and has the ability to handle pallets without human intervention. Roodbergen and Vis (2009) have proposed that the main function of ASRS is to moderate impact during the selection of cases and retrieve them in a precise direction and sequence. ASRS functions as a sequencing system to allow a random stream of picked cases to be buffered and re-sequenced. This sequencing machine makes it possible for the operator to select each case within the buffer, and it would be the best alternative method, especially for traditional picks to the belt system in mix case approaches.

Lerher et al. (2007) presented a computer aided design for an automated warehouse, including multi-objective optimization of ASRS. They decided to optimize time, cost and quality. There are many categories of ASRS, which support to automate full-case picking. Single mast and single shuttle ASRSs are the common types which have been used by many automated material handling industries. This technology could lead to more advanced processes when it is mounted with telescopic forks. These telescopic forks help to store pallets at different depths on a rack. The single mast dual pallet has the ability to transfer double pallets at a time. Usually, this technology is performed in surroundings in which pallet sizes are fixed, but the necessities of items passing through a process are high, and therefore, this technology is applicable for warehousing which requires a high variety and number of SKUs.

The aisle-changing ASRS facilitates the process of utilizing this system for companies, as it requires low investment. Apart from that, this technology enables the respective cranes to perform with multiple aisles in the warehouse. It is possible to use fewer cranes than aisles in a system. Roodbergen and Vis (2009) clarified that this type of technology effectively needs a large space, especially for an area for changing aisles in order for the crane to move into and out of the storage. Originally this technology was developed to provide greater convenience, particularly in the beverage industry with heavy pallets. It is effective to apply this technology in an industry that requires a higher level of throughput and also produces a higher output volume. This technology is designed to generate a very large number of throughputs by transporting pallet pairs in an effective way. Cranes can deliver two loads by using dual-shuttles, or may shuttles to carry more than two loads.

This technology was greatly enhanced to high speeds to double the throughput rate. Depending on the size of the warehouse, these machines are able to generate pallet throughput of more than 75 pallets per hour. An excellent storage system has a complete range of satellite ASRS which are mounted to the ASRS machine in the warehouse and storage environment. This satellite carrier is highly advantageous in reducing handling time as well as increasing comprehensive productivity, however, the main function of this technology is to transport the pallets in very dense storage with minimal building footprint.

For a highly efficient warehouse, a satellite carrier is used to allow the actual storage and retrieval function in the storage lane with good performance. In another scenario, the ASRS machine is equipped with a shuttle carrier that is efficiently designed to expedite the handling of throughput in high transaction environments. It is also highly flexible for automated storage and retrieval of the pallets in single or multiple depths. In other words, shuttle carriers allow more storage in less space and are sustainable for higher throughput requirements. This technology can be powered by a shielded umbilical cord, or equipped with a rechargeable battery. Both these technologies are applicable in the food and beverage industry because the production line generates many pallets from the same item. Gilmore and Holste (2009) also suggested there could be an alternative ASRS method in which human order pickers ride the crane that moves automatically into a series of full pallet storage units.

ASRS could also be used for downstream piece picking activities. This method is good for delivering cases for piece picking activity and is fully ACP, however, it is a bit slower in moving SKUs and generally not good for fast-moving SKUs. Lerher (2006) designed and evaluated the class-based multi-aisle ASRS, and Khojasteh-Ghamari and Son (2008) developed a solution to solve problem in a multi-aisle automated warehouse served by a single storage and retrieval system. They proposed an algorithm to reduce the average travel time of S/R devices. Lerher et al. (2007) suggested the same idea, for multi-aisle automated warehouses. One S/R machine can be used to service more than one aisle to accomplish automatic aisle transference. Vasili et al. (2012) have reviewed many travel time models and control policies based on ASRS.

In their book 'Warehouse and Distribution Science', Bartholdi III and Hackman (2010) explained that ASRS removes human operators, where new robotic devices are installed in the workplace and travels in each aisle in the warehouse. This device allows movement in horizontal and vertical directions through a single command cycle or a dual command cycle in order to store and retrieve unit loads. In order to perform a dual command cycle, a unit-load is stored first, and then continues to retrieve another unit-load by using the S/R device. Roodbergen and Vis (2009) suggested that a multi-shuttle crane with telescopic extension is used to support two or more loads at a time.

ASRS is able to eliminate manual material handling demands and repetitive handling tasks, increase throughput, and significantly reduce product loss. Normally this system can be used with a variety of picking options around rack systems and machines with respect to optimizing warehouse functions and attaining the optimum space utilization rate. ASRS technology is used to achieve extremely high storage density as well as to reduce labor costs. O'Shea (2007) reviewed the literature by developing two physical models of ASRS simultaneously, in order to prove the results of a mathematical model. This helps to clarify further discussion on pay progression strategies with interested parties and make effective sequence operations. Gagliardi et al. (2010) suggested that one of the most appropriate ways to model for ASRS was by using a simulation approach. This simulation is more precise and is rarely generalized across a large number of sites.

2.3.8 Summary of previous literature

Many companies experience competitive pressure in the market, to respond to short term variations in time, enhance accuracy and be careful to avoid losing precision. A huge number of retailers request logistics to increase their shipping rates. Most internet retailers are looking forward to many successful automated picking systems, since automation plays such an important role in the future of order fulfillment. Basically, the automated picking system can be explained as the process of retrieving items automatically based on specific customer orders.

According to overall sales, it can be concluded that such an ASRS shows a consistent rapid growth in market share. Carousels and robotic devices have also experienced consistent rapid growth, and conveyor systems retain and maintain their share of the market. At the current time, overhead conveyor systems and AGVs no longer have a share of the market, with growth that is over the general level of inflation (Baker and Halim, 2007). Many logistic researchers base certain categories of research on automated full-case OPP. A viable approach which has been used through this case study is to deliver modifications of the objective function, optimized for creating economic value by design. In this section, two case pick solutions have been selected as the best tools to support full-CPS.

First of all, many companies are growing more aggressive about building their distribution and content delivery worldwide. The utilization rate of gantry robots has drastically increased, however, it seems that the automated material handling industry in general has introduced the same solutions with slight differences according to the development of robots in the warehouse. A combination of robotic gantries, conveyor systems and intelligent software is an alternative way to automatically pick full-case. Gantry robots are relatively new technology for automated picking systems. The use of robotic gantries will deliver huge benefits to automated handling system industries. Generally, this technology is capable of eliminating the time wasted by concentrating on bottlenecks, thus there will be less work to carry out. Accuracy and precision are definitely defined where attribute information can be specified.

Companies have an opportunity to increase their profit as the amount of product loss is reduced. The space utilization rate can be significantly maximized. The most important advantage of gantry robot technology is definitely that it is an ACP process without any human intervention. Human error thus does not exist. Automated gantry robots are able to trace and pick cases in high speed picking operations and have the ability to select numerous different types of SKUs from different locations.

Ata et al. (2009) have designed and developed a gantry robot to automate storage and retrieval processes. They designed a gripper tool for robotic picking into accurate boxes by using a light sensor that made it possible to pick the case at high speed. The products are then sorted and stored based on a moving conveyor belt. Li and Masood (2008) have presented methodology and a research approach to queuing models with a high speed palletizing process involving two robots which provide the dynamic flow of the system. Talpur and Shaikh (2012) presented a robotic system for the small food industry, which minimizes the cost and eliminates manual tasks.

Horizontal conveyor based systems are used mainly to develop solutions for designing, modeling and controlling the system, and at the same time, to quantify and to improve throughput and flow time performance. Today, many companies use the principle of a belt conveyor, but one that is more advanced and fully ACP. The system is the most commonly used, and has well-established production facilities because this system has been around the longest. Its main purpose is to reach the maximum amount of throughput. Concerns have been raised related to operations such as increasing demand enclose with replenishment and fulfillment because many companies have a strong interest in this method.

Andriansyah (2011) presented an end-of-aisle OPS. The alternative is to emphasize out of sequence arrivals, and by having multiple storage racks separated from workstations there are benefits where items for multiple orders can be retrieved simultaneously, allowing a greater number of SKUs. Basically, the physical structure of these OPSs consists of mini-loads, workstations and conveyors that connect the mini-load area to the workstation area. Mini-loads are mounted with cranes to store and retrieve items. Each crane has the ability to store and retrieve four items at a time. There are five mini-loads present in this system. Workstations consist of three input buffers and one output buffer, however, in order to perform one customer order at a time, a human picker must be present in the workstation, because multiple orders arrive simultaneously. A bottleneck can occur across the entire OPS, where an effective picking policy has been created based on nearest-to-the-head, nearest neighbor, dynamic programming and backward search. The replenishment approach used through this system is based on an order-point, order-quantity system.

Bleifuß et al. (2012) presented the development of new storage and picking technology. The process involves the tray being retrieved from the storage area using ASRS machines, however, the tray cannot be handed over directly to a wheeler lift, and is placed first in one of the transfer locations. A wheeler lift then collects the tray and transfers it to an intermediate buffer belt. The cases are picked according to customer orders from the tray, using a specific wheeling mechanism, and are transferred to the intermediate buffer of each collecting conveyor. This technology provides a specific full-case picking approach. The process of replenishment is based on incoming pallets, which are dispatched by suppliers, and transferred into a pallet storage area, where each of the incoming pallets delivers different layers of cases for a single SKU or rainbow pallets with one SKU per layer. The process is continued by automatically transferring each layer from the pallets on a tray. These trays are then delivered to the storage area in the warehouse. The location of each tray in the warehouse is known as its STS. The system delivers a proven concept, using a mature system.

It can be concluded that, both, gantry robot and horizontal conveyors are automated systems in order to retrieve and deliver full-case picking. By applying gantry robots in warehouses, minimum space is required throughout the warehouse, if compared to horizontal conveyors, however, a horizontal conveyor in most cases has the ability to transfer different case sizes and weights, whereas gantry robots usually bring only heavy loads. Horizontal conveyors are not consistent in their performance because it takes such a long time for maintenance, in which the conveyor system needs temporary closure and the maintenance costs are quite high. The most common reason for this failure is that broken pieces of pallets can obstruct the conveyor system from moving forward, however, gantry robots are not applicable in case of weak container base and might not be appropriate for fragile products.

3 AUTOMATED CELLULAR CASE PICKING SYSTEM

This chapter describes an idea for a new automated full-CPS. The requirements of the new design are identified; the problem solving methodology is described. ACCPS structure, operating principle and control aspects are identified, analyzed and discussed in detail.

3.1 Introduction

The OP is one of the most important logistic processes in a warehouse. This system is of high importance in OP operations, where the prime focus is customer satisfaction, and this drives OP as one of the most controlled logistic process. The cost of the picking process could reach up to 65% of the warehouse operating costs. In fact, the retrieval cost exceeds the storage cost of any given item (Coyle et al., 1996). The efficiency of the OP system depends on various factors, of which product demand, the warehouse layout, the location of items, the picking method in combination with the routing methods, the experience of the employees, and the extent of automation play major roles (Gattorna, 2003). The prime challenge for OP systems is to "minimize - order retrieval time" which steers the requirement for any OP system. The travel time to retrieve an order is a direct expense, but it does not add value. It should be noted that in many OP situations, minimizing travel time is an objective for improvement. It is usually realistic to assume that travel time is an increasing function of the travel distance in the case of manual picking OP systems (Hall, 1993 and Petersen II, 1999).

ACCPS is a new ACPS where all OP activities are fully automated. It has been developed for handling products in plastic crates, bins, boxes, or bins. This system is ideal for applications with a large volume of cases to be picked on a daily basis. A typical application could be found in areas such as DCs and factory warehouses (e.g. retailers, dairies, bakeries, meat processing plants etc.). ACCPS is a new design for improving warehousing performance, measured in terms of utilizing the minimum storage space for specific purposes and also improving productivity. Its robust design would be instrumental in reducing cycle time, increasing accuracy, and decreasing the operating costs of the OPP. ACCPS is designed based on the ASRS design problem that focuses more on the operating throughput and the utilization rate of the storage area. The main idea of the new design will be described in detail, based on logistical, mechanical and processes controlling requirements, and supported by explanation of the operating principles.

3.2 Design Requirements

ACCPS is particularly designed to organize picking and restocking the inventory in order to optimize the product flow during the CPP. The most challenging issue facing any OPS is the travel time involved. In manual CPSs much manual labor is required for repetitive handling and picking the SKUs, and has become an essential part of the process within high order volume DCs. Automated full-CPSs have thus grown rapidly; small warehouses are replaced with larger warehouses supported by new technologies that are constantly improved to cope with the new challenges. These technologies contribute to achieving higher productivity and demonstrate an increasing growth rate.

There are many reasons that companies may be interested in automated full-CPS. The main reasons include avoiding dealing with labor, improving customer satisfaction and reducing operating costs. The most important reason for choosing fully automated CPSs is to minimize both operating cost and staffing levels. Interestingly too, the automation contributes to achieving maximum throughput and maintaining high levels of accuracy. Automated full-CPP can be considered the most significant contributor to managing the demands of high volume environments in many warehouses and DCs. Full-CPP basically refers to a very complex design for procedure handling, which includes a complete analysis of the system and the equipment confined within it. The ability of a company to make quick improvements (e.g. by using a new ACPS or a new technology) depends on the applied automation level in its activities. There are many ways in which research can be conducted with regard to designing effective automated full-CPSs.

According to Groover (2001), the goal of a material storage system is to accumulate materials for a certain time and to permit access to those materials when required. The performance of OPS in accomplishing this function must be acceptable in order to justify the investment and operating expense. Various measures are being used to test the performance of the OPS:

- *Storage capacity* (the total available space volume or the total number of available storage compartments in the system)

- *Storage Density* (the proportion of used volume from the total available volume)
- *Accessibility* (the ability to access any desired SKU in the system)
- *Throughput* (the rate of storage and/or retrieval processes that the system can manage in a unit of time)
- *Utilization rate* (the proportion of system's used time from total available time)
- *Reliability* (the proportion of time where the system is ready to work, from the total time).

A combination of the standard problem-solving methodology and the proposed methodology to solve OPS design problem by Yoon and Sharp (1996) and Dallari et al. (2009) can be used as the basis to solve the proposed ACCPS design problem. The standard problem-solving process has six steps as follows

- Step 1. Identify the problem
- Step 2. Analyze the problem
- Step 3. Generate potential solutions
- Step 4. Select and plan the solution
- Step 5. Implement the solution
- Step 6. Evaluate the solution

The first two steps lead to identifying and analyzing all requirements with an effect on the research problem and which can help to identify and understand the problem from all aspects. There are three categories of requirements that can be classified to identify the research problem: logistical requirements, mechanical requirements and process controlling requirements.

3.2.1 Logistical requirements

Rapid expansion and industrial growth makes new demands on science and technology. During a logistics process, products (raw material, goods-in-process, finished goods) may be buffered or stored at certain places (warehouses) for a certain period of time. Automated warehouses increase the utilization rate of the space, saving operating costs and improving the customer service level. Automated OPS can maximize the efficiency of warehousing and logistics, to meet customer demands, and to create the greatest economic value of the company in a competitive environment in a favorable position. The use of computer controlled management has become indispensable for logistics and production management. More and more companies have adopted automated warehousing system as the first choice for their storage. In order to satisfy different requirements from different customers, constantly improving and optimizing automated warehousing systems is necessary. The assumed logistical requirements for the new design of ACCPS are as follows

- Increasing storage capacity and density: it must be greater than the alternative solutions. To achieve these goals, the footprint of the solution is minimized by exploiting the height of the warehouse and by minimizing the floor space.
- Improving accessibility: the new design should have access to all SKUs in the system at one time, and this is the core advantage of the new design. While accessibility is a feature in most of the alternative solutions, it is never more than one SKU at a time. To tackle this issue, there is an alternative solution (horizontal conveyor based automated picking system, see Section 2.3.4) which allows full accessibility (to all SKUs at one time), but the total throughput of this system would be very low in comparison with the SKU flow rate from the storage compartments. This could be because of the bottleneck of this solution at the mixed palette building station or because of low feed flow to this station. To avoid this problem a constant flow rate is considered in the new design.
- Increasing throughput: the throughput of the new design should be very high compared with the alternative solutions, as a result of the full accessibility of the new system to all SKUs at one time, and also because of the constant flow of the SKUs in the system in all stages.
- Decreasing operating costs: the operating costs of the new system must be lower than in manual systems and other available automated systems.
- Increasing flexibility: the flexibility of the new system must be very high in order to handle most operational scenarios, order fluctuations, and future growth and changes.
- Improving the utilization rate of OPS: the utilization rate is the amount of time used by a production facility relative to its capacity.
- Increasing accuracy: the accuracy of the new system must be better and should achieve 100%.
- Improving customer service.
- Improving stock rotation.
- Decreasing the number of damage products during the operational processes.
- Improving the safety of storage.

- Improving ergonomics in the warehouse.
- Decreasing order cycle time.

3.2.2 Mechanical requirements

Automation seems a feasible solution to improving productivity, quality, or other measures of performance. Automation is a great opportunity for reducing the non-productive periods that exist in warehousing systems. There are logistical limitations, as there are also mechanical requirements in order to design optimal OPS. The mechanical requirements to be considered are as follows

- Increasing the rate of ROI in order to justify the high investment costs. This rate must be high and acceptable.
- Improving the robustness of the OPS.
- Decreasing the system construction costs by using the standard mechanical components and subsystems to build the whole system.
- Decreasing energy consumption: the best way to decrease energy consumption in the area of material handling operations is by increasing the ratio of payload to dead load as much as possible.
- Simplifying the mechanical systems to decrease maintenance and installation costs and time.
- Increasing the flexibility of the mechanical systems to work as individual modules, for which the whole system would possess more flexibility in order to work under any conditions and scenario.
- Increasing availability: availability is a measure of system reliability, defined as the proportion of time that the system is capable of operating (not broken down) compared with the normally scheduled shift hours.

3.2.3 Processes controlling requirements

Increasing demand in the market, the breadth of diversity and the intensity of competition demands continuous improvements of logistics processes, which in turn decrease logistics costs and increased logistics performance. WMS and WCS are integrated in order to satisfy all logistical requirements of the OPS, and therefore, these systems must satisfy all processes controlling requirements, which are as follows

- Improving control over inventories
- Flexibility of management and the controlling system to adapt OPS in order to reduce the effort for changed processes in intra-logistics
- Process orientation in order to execute the operational scenarios
- Process control and optimization
- Plant operations and control
- Integration of operations
- Adaptation according to strategic and operational performance requirements
- Adaptation in order to avoid system breakdown

3.3 System Structure Development

Many companies and industry sectors involve large-scale movement of daily goods entering and leaving their warehouses and DCs, and the main type of OPP handled in these sectors is the full-CPP. According to Balakirsky et al. (2010), the most typical scenario in warehouses and DCs is receiving pallets containing a single type of SKU, de-palletizing the product, and then creating new mixed SKU pallets for transport to customers. About 30% of 140000 containers that are imported into the US per week are immediately repacked onto mixed pallets for distribution to stores, and half the more than 80 million SKUs for the grocery industry are distributed to stores per week. According to Faulkner and Murphy (2010), the "holy grail" of warehousing and DCs is the automation of this operation, which has the greatest labor costs, the greatest potential for product damage and where the order inaccuracies of manual labor are most prevalent. According to Gilmore and Holste (2009), the companies that handle between 20000 and 40000 cases per day during peak times have a high or fairly high level of interest in ACPS and level of interest of the companies that handling more than 40000 cases per day during peak times jumps to 20%.

According to Gilmore and Holste (2009), a medium case picking volume is defined as more than 20000 cases per day at peak periods, and a high case picking volume is defined as over 60000 cases per day at peak volume. If the average daily handling volume is about tens of thousands of cases, of no more than hundreds of types of products (SKUs), standard and stackable handled cases, this situation has a very high potential for automating and designing a flexible ACPS. Actually, there is no single solution that can be adapted to all sectors. Because of the diversity of the operational environment, some solutions are suitable for warehouses and not others. In the case of the indirect picking process (see Section 1.2.6), the incoming pallets of products (one type of product) are split into cases. These cases are automatically stored in a buffering area and then the required SKUs are automatically retrieved in sequences according to the customer request. Ultimately a new mixed SKU pallet is built and delivered to customers. The next two steps of the standard problem solving process alongside the OPS design methodology proposed by Dallari et al. (2009) led to the creation of the new OPS.

3.3.1 System layout design

With the rapid development of the concept of the supply chain and lean manufacturing, suppliers are searching for more and more efficient storage and retrieval methods. “Perfection is not attainable. But if we chase perfection, we can catch excellence.” says Vince Lombardi, a well-known American football coach. To achieve this goal, many warehouse technologies have been developed and applied, include new tools and new concepts of management, such as picking strategy. The best method, however, has not yet been found, or we could say that the best method does not exist, because there’s no single solution that can solve all problems. For specific conditions, however, the best solution can be found.

One of the main functions of a physical distribution warehouse is OP, the process of identifying, selecting, retrieving, and accumulating the proper items for customer orders (Coyle et al., 1996). The current grocery industry involves fast-moving consumer goods, updates fast, has complex and diverse needs. It has long been identified as a very labor-intensive operation in manual systems, and a very capital-intensive operation in automated systems. Improving the speed of automatic selection could be realized by understanding company warehousing and the OPS of the actual demands and actual situations. Actually the core of the most of nowadays ACPS is the ASRS stacker crane principle. The limitations of this kind of technology, according to research problem requirements are:

- The high investment costs: a mini-load stacker crane costs: about 120,000 Euros (Heinz et al., 2004)
- The throughput limitation of the stacker crane (not more than hundreds per hour)
- Higher energy consumption due to the high dead load (high mass of stacker crane)
- Low accessibility to SKUs at one time (usually not more than one SKU at a time)

The superior features of the new system are able to overcome these limitations. A new system with the same principle as the A-Farm system would be a very good solution to most problems of ASRS system. An A-Frame is an automated picking or dispensing machine that tends to be used in DCs. To fill an order, the dispenser channels under computer control drop small individual items of uniform size and shape onto a conveyor or box. Typically, this system straddles conveyors that support small part high volume OP, and are largely used for cosmetic or pharmaceutical products.

The system only performs for each single order, where items are automatically released from the frame (channel) and conveyed to the collection workstation. By redesigning the A-Frame principle in order to handle large SKUs such as standard boxes, crates, or crates and cartons, a new innovative automated full-CPS can be created. The channels (cells) in the new system are redesigned to fit in the new SKU profile. The construction of the new cell can be the same as that of the vertical indexing conveyors (VIC) or elevators which are used to change the case flow levels. By using the standard VIC as a buffer system for cases (cells), many cases (SKUs) can be stored in one cell, depending on the height of the SKU and the height of the storage cell (see Figure 3.1).

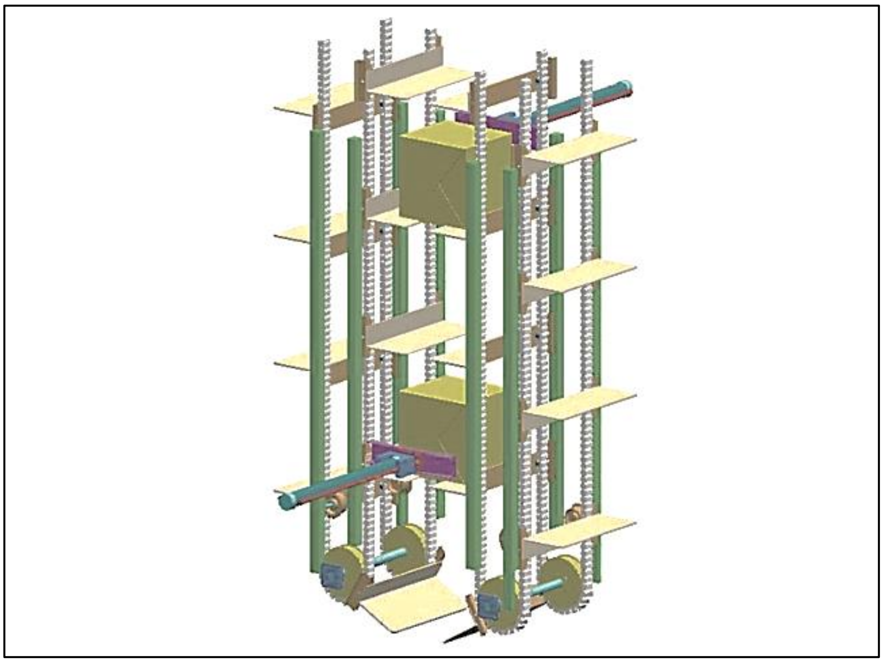


Figure 3.1 Vertical indexing conveyor (NERAK 2015)

Many cells are installed together in one row to form a storage line. Part of conveyor passes through the VIC to feed the cases, the same principle is used here to feed the cases to cells; a conveyor passes through all the cells that are installed in the same row. Many storage lines can be built together to form an ACCPS (see Figure 3.2). The dimensions of an ACCPS are determined according to many factors, such as SKU dimensions, required throughput, available investment costs, etc.

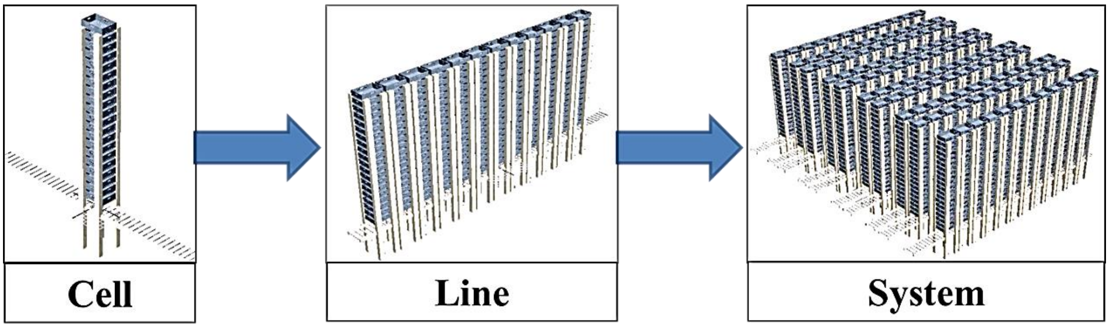


Figure 3.2 ACCPS structure-forming phases

For most ACPSs, uniform and standardized loading containers (plastic crates) are generally used. The products are manufactured and may be packaged, and are then put in special crates. The crates are usually arranged in stacks. These stacks can be aggregated on one platform (pallet). Pallets are the most basic platforms used for handling and transporting goods as a unit-load. There are many pallet sizes. The most famous and standard pallet board is the American standard pallet size, which is 1200mm long and 1000mm wide, and the European standard pallet size (Euro-pallet), which is 1200mm long and 800mm (ISO 3676, 1983). (see Figure 3.3).

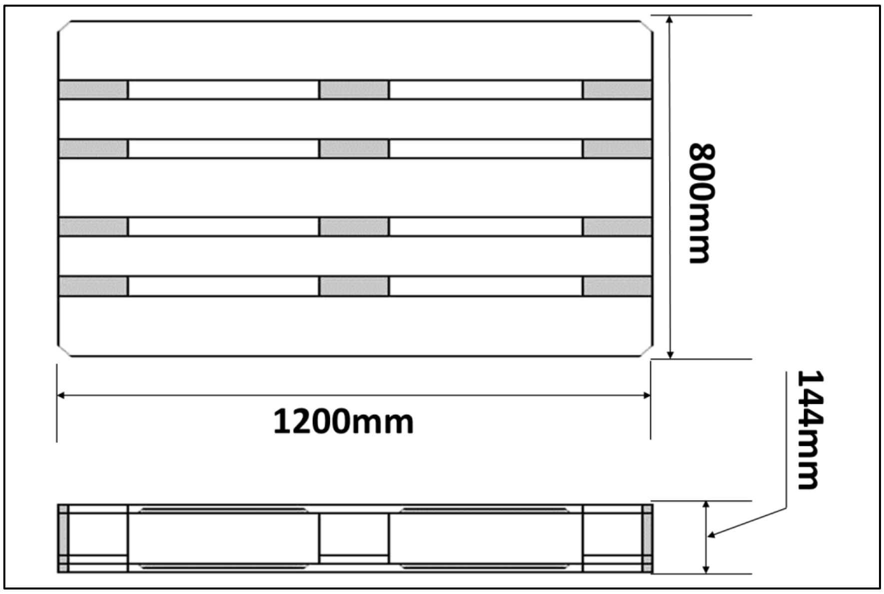


Figure 3.3 Euro-pallet structure (ISO 3676, 1983)

The pallet size considered in this research is the Euro-pallet. The dimensions of the most commonly used crates for the Euro-pallet are standards, especially in the grocery, retailing, and other DC sections. Based on the crate base dimensions, there are two standard European crates suitable for the Euro-pallet (ISO 3394, 1984). The first one has base dimensions of 600x400mm and the second one has base dimensions of 400x300mm. The heights of these crates are from 140mm up to 420mm (see Figure 3.4).

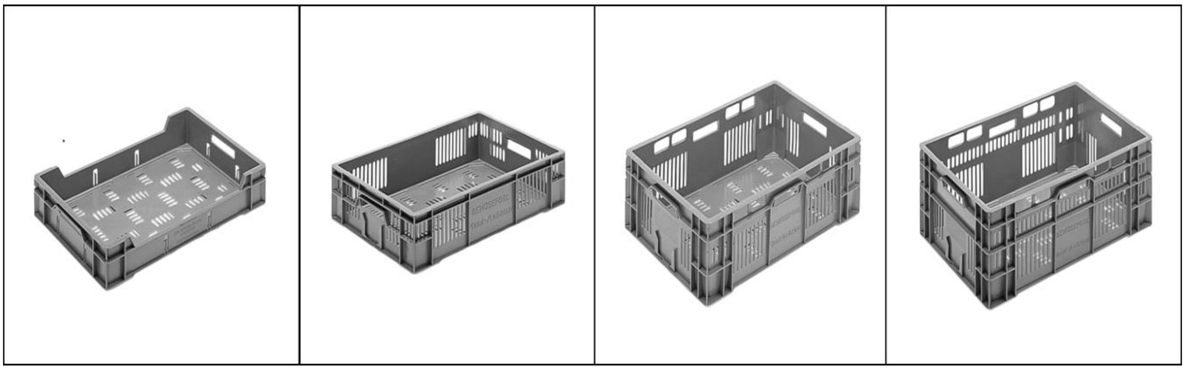


Figure 3.4 Standard crate (Bekuplast GmbH)

In the industry, plastic crates are widely regarded as the "perfect" container for conveying products. They are consistent in dimensions and weight, meaning they are easier to handle than other material forms. They are stackable, ergonomic, clean, and reduce the cost issues associated with damaged products. They are suitable for RFID technology as well as use with barcodes and security ties that are instrumental for safe shipping.

The items that arrive at DCs in bulk packages (pallets) will be stored in the reserve area. The required pallets are transferred to the ACCPS (using forklifts or other facilities). These pallets are disassembled into stacks; these stacks are unstacked into crates before reaching the cell area on the storage lines. The unstacked crates are horizontally conveyed to a certain cell installed on a storage line. If the crate reaches the cell, a stop actuator is released to stop it in the boundary of this cell, then the elevation system takes it up one step to store it in the first location within the cell. The next crate passes into the cell and so on until the cell is completely filled. To retrieve the crates from the cells, the rotational direction of the cell elevation system is changed in order to move the stored crates one step down. If the first crate is placed on the conveyor, it will be released, and then it will be transported horizontally to the next stage. When the first crate is out of the cell boundary, the next crate can be released. All retrieved crates that come off a storage line will be stacked by a stacker machine installed at the end of this line; these stacks could be full-stacks or small-stacks. These stacks are automatically conveyed to the accumulating conveyor, which has a palletizing machine at the outlet, this machine aggregates the stacks onto the pallets. In order to minimize the number of pallets delivered per customer, a re-stacking machine (full-stacker) is installed between the stacks and the palletizing machine. The re-stacker aggregates the small-stacks into full-stacks. (See Figure 3.5)

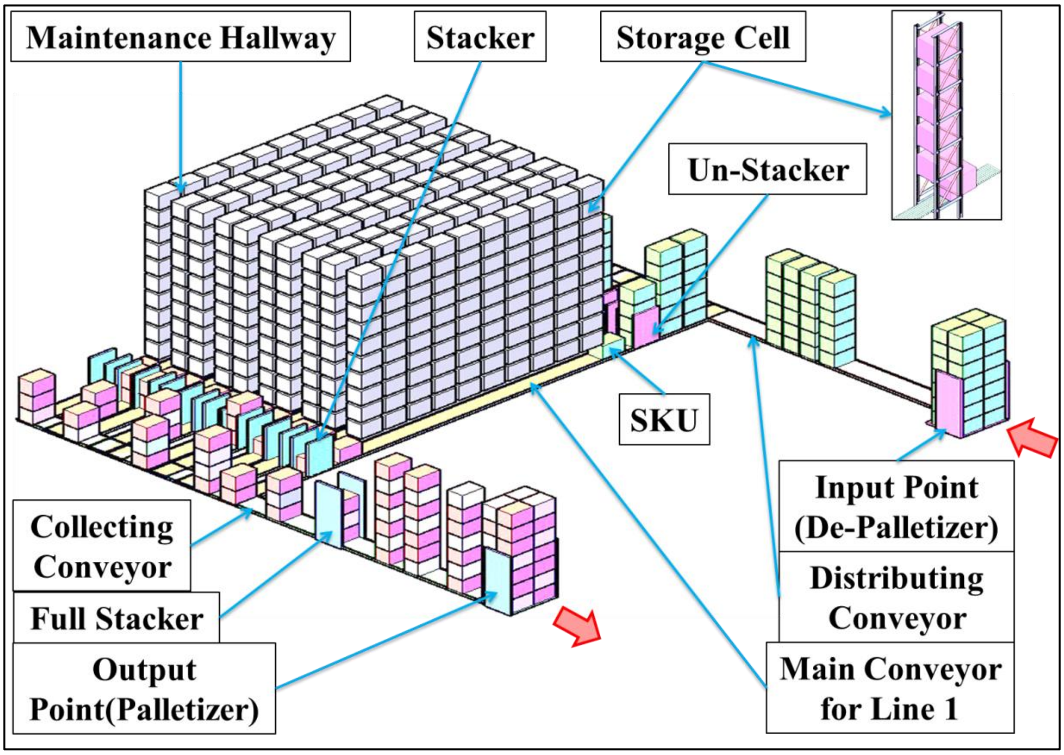


Figure 3.5 3D Layout of the ACCPS

The layout of the ACCPS is divided into three different areas: the input area, storage area, and output area, where the design of every area depends on many different factors. Designing the input area mainly depends on the form of the incoming goods and the required capacity (i.e. throughput) of this area. The design of the storage area mainly depends on the profiles of the crates handled and the orders, however, the design of the output area mainly depends on the type of packaging of the customer's delivered products and required capacities (such as available areas, requested order cycle time, etc.) (See Figure 3.6).

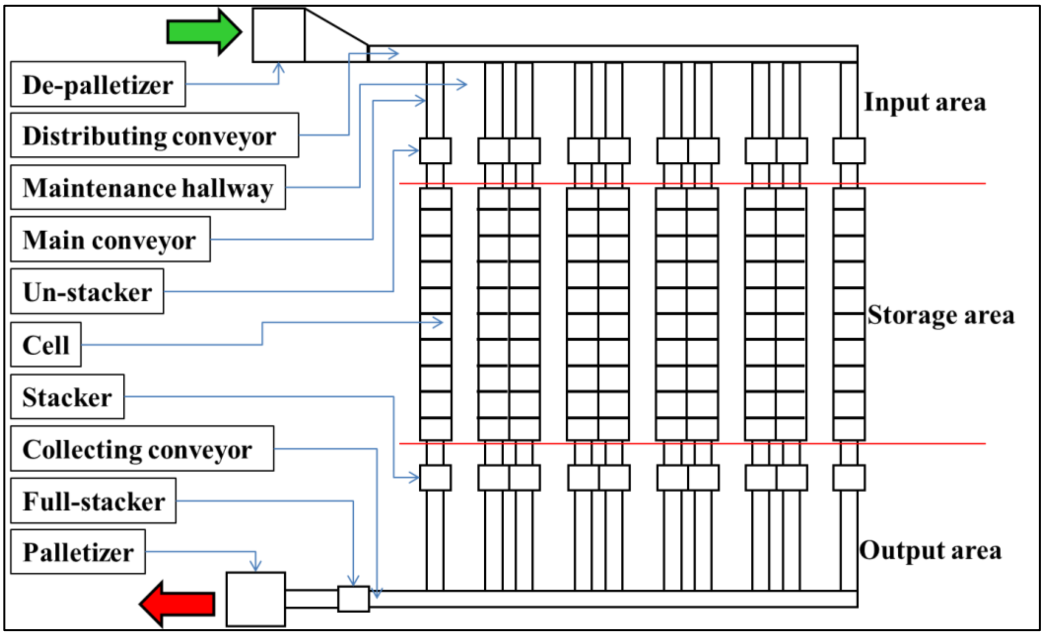


Figure 3.6 Layout of the ACCPS and the system's main parts

The basic idea of this new system is the "cell", which is forms a multiple-depth high-bay storage rack for standard cases. The cell consists of many storage locations, where the dimension of each location can be adjusted according to different requirements. The cases (e.g. plastic crates) are automatically moved horizontally and vertically by two conveying systems. The layout of the whole ACCPS is designed according to specified requirements (see Section 3.2). Based on the dimensions of the crates used, the mechanical structures of the cells, conveyors, and other parts of the system are designed. The technical specifications of all system components (i.e. the storage cells, conveyors, and the other parts) are determined according to the required throughput, system capacity, storage and retrieval strategies, etc. The layout of the whole system is subsequently determined.

3.4 System Operating Principles

According to Gilmore and Holste (2009), OPS design is a very complex task due to the wide variety of design requirements and criteria. These requirements are related to SKU profile, order profiles, facility constraints, cycle times, and internal constraints, and therefore it is very important to describe and analyze every process separately, from the point where the products enter the system to the point where the products leave the system. The design of the ACCPS is focused on the cases of incoming pallets with one SKU per pallet, where there are many stacks in one pallet, and many crates in each stack.

The basic concept of this new OP is designed in a similar way to existing OPS such as horizontal conveyor based- and robotic systems. The items that arrive to DC in bulk package (pallet) form will be transported to the OP area, where they will be disassembled into stacks. The stacks are disassembled into cases. These cases will be sorted and stored for a certain time, then are retrieved according to customer orders. The cases picked for a customer will be re-palletized before being shipped to them. If the required cases for a customer order are not all immediately picked, this customer could be reserved for a certain time in a temporary storage area, until all required cases for them are picked. The flowchart in Figure 3.7 explains the basic operating principle of the ACCPS.

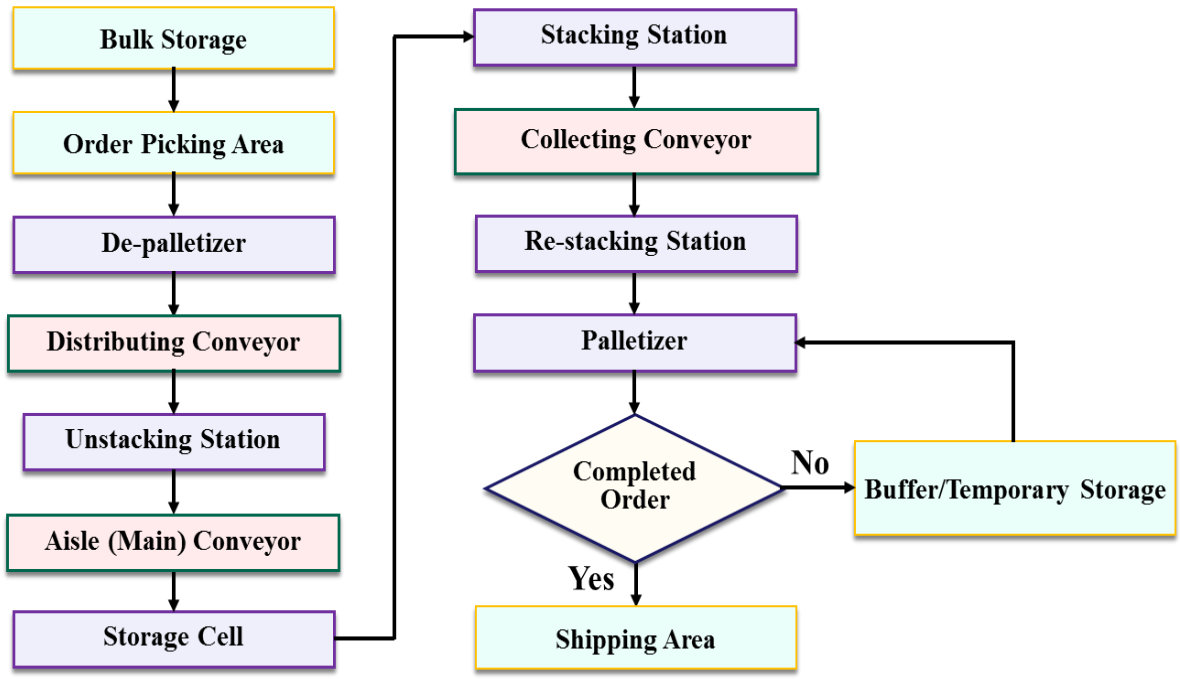


Figure 3.7 Flowchart of basic operating principle of the ACCPS

The storage process involves splitting the full pallet into stacks with a de-palletizing machine, where these stacks are transported by a distributing conveyor to a certain storage line. At the entrance to this line there is a de-stacking machine to split the stacks into crates, and then these crates are transported by a main conveyor to the specific storage cell. The cell takes the first crate up using an elevation system mechanism, followed by the next crate, and so on until the cell is full of crates. The capacity of the cell depends on the cell's height and the height of every storage position within the cell. The height of the storage position with the cell is determined (i.e. crate height plus 5-10cm as tolerance) according to the heights of the handled crates. In full-CPP, cases of one or more kinds of products are retrieved from their storage cells and moved to the next process step (i.e. stacking). That means that the last crate that enters the cell will be the first that leaves it. This operating strategy is known as the 'last in first out' (LIFO) strategy. All retrieved crates from a storage line - order by order - are re-stacked again into small or full-stacks by a stacking machine installed at the end of the main conveyor. These stacks are aggregated from the main conveyors and conveyed to a collecting conveyor according to the required sequence. These aggregated stacks are transported to a full-stacking machine that stacks the small-stacks into full-stacks if necessary. Every four full-stacks are collected on one pallet by a palletizing machine installed at the outlet of the ACCPS (see Figure 3.8).

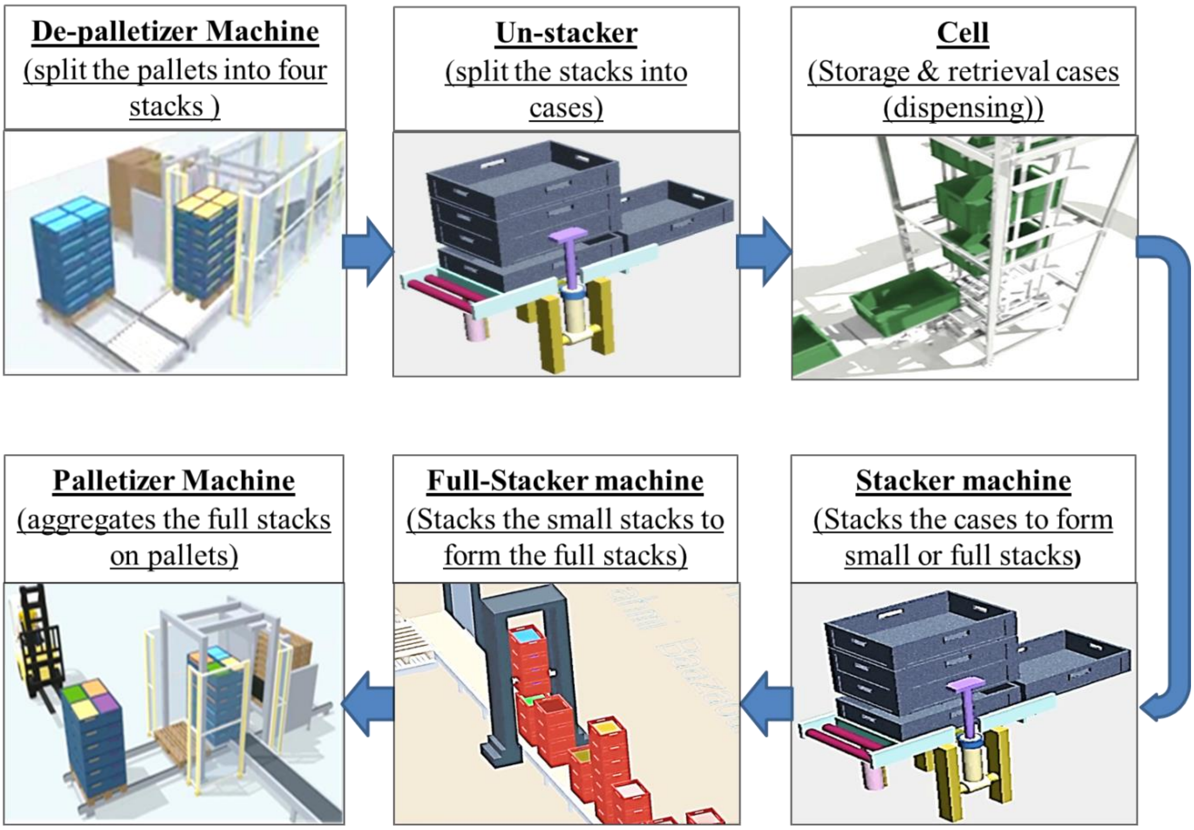


Figure 3.8 The basic phases of ACCPS operating principle

The stacks emerge from the main conveyors in batches. Every batch represents a customer order; the size and time of each batch depends on the customer order and the availability of the required products in the cells. For efficient performance, is it assumed that only one type of product is stored in a storage cell, and a replenishment process is executed if the cell is empty or close to being empty, which depends on the capacity of the cell and the crates number of the replenished pallet. The expected required pallets are prepared near the input point of the ACCPS. A new full pallet is fed to the entrance of the ACCPS. Many expected operating strategies will be discussed in the following sections.

3.4.1 ACCPS filling phase (put-away process)

The filling phase of ACCPS is the put-away process to store the SKUs in their storage locations within the cells. The filling process can be divided into two types according to the running time. The first type, the filling process, has an independent time. That means that there is no other process happening in the system at the same time as the filling process. The second type, the filling process, does not run on independent time. The picking process could begin parallel to the filling process. According to these classifications, there are many scenarios that could be executed.

- ***Filling process with an independent time***: the simplest scenario is to fill all cells and then start to pick up the required crates to satisfy the customer orders. That means that the whole process is divided into many independent times: independent time for receiving products or producing them (if it is a warehouse in a production facility); independent time to store the received products either in the bulk storage (reserve area) and then in the ACCPS, or directly in the ACCPS; independent time for receiving the orders from the customers; independent time for picking the required crates and packaging; and independent time for delivering the picked products to the customers. There are overlaps between these processes, but the critical point is that there is no overlap between the picking and the filling processes.
- ***Filling process without an independent time***: this means that there is an overlap between the processes, especially between the crate storage process and crate retrieval process. Because of the exceptional design and the high flexibility of the ACCPS, many operating scenarios and strategies could be applied. For example, it is possible to start the filling process in the first cell of every storage line from the output side. When these cells become full, the filling process is shifted to the next cells. At the same moment the OPP could be started, where the required crates from the articles stored in these first cells would be retrieved. Every newly filled cell could enter the picking phase directly until the last cell on the storage line (storage and retrieval process at the same time). This scenario has many advantages, such as duplicating the throughput, minimizing the operating costs, etc., but at the same time it has disadvantages, such as the complexity of controlling the scenario, the paucity of suitable application environments, and the extra requirements (such as the required areas before and after the ACCPS).

Actually, many factors have an effect on the decision to select the best filling strategy, such as the nature of the handled products and nature of the warehouse (production warehousing or DC). Otherwise, if ACCPS is a part of the production system, the crates that leave the production lines can be directly stored in the cells, and if the cells are full, the extra crates produced can be aggregated on pallets and stored in the reserve storage area, then later fed to the ACCPS as required.

3.4.2 OP strategies of the ACCPS

A retrieval process is needed only when a customer order is received. All data is inserted to the WMS, and then the data will be analyzed and a decision made to determine the availability of the required crates and articles. Based on the information of the WMS, the WCS identifies the cells that have the required articles, and the retrieval process is started by moving the elevation systems of these cells with the stored crates one step down. According to the LIFO strategy, the latest stored crates are placed on the main conveyor; these crates will be freed from the elevation systems and transferred horizontally to the next step. This process will be repeated until all required crates are retrieved from the cells. The retrieved crates are transported directly to the output point of the main conveyors, where there is a stacking machine on every point. These machines aggregate all retrieved crates into stacks, where these stacks are conveyed to a collecting conveyor. This conveyor feeds a palletizing machine, which aggregates these sacks on pallets. In order to minimize the total number of pallets delivered to a customer, a re-stacking machine is installed between these stacks to re-aggregate the small-stacks into full-stacks.

The priority of the retrieval process for the cells located on the same conveyor can be selected and controlled automatically by the WMS and WCS. This priority could be changed to reach a specific sequence for the picked articles. Similarly, the feeding priority of the picked stacks to the collecting conveyor is controlled to reach the specific sequence of the picked products. There are many scenarios that could be executed to fulfill the customer orders. The most common scenarios are related to the filling process as follows

- ***If the filling process is complete (all cells are full), OP is started* -** this scenario can be executed only when all cells become full. The availability of the required crates for a customer order is checked. If all required crates are available, they are picked up immediately and then a new customer order can enter the system. If they are not, perhaps because the available quantity (number of crates) is not enough or the required articles are not in the system at that time, all available required crates are picked up, and a new replenishment process could be started. A new checking process would therefore be executed, to determine whether the new required crates become available or not. If the answer is yes, the available crates would be immediately picked up, then, a new checking process is executed, whether all required crates were picked up or not. If the answer was yes, that means that the OPP for this customer is complete and the picking process for the next customer could be started. If the answer was no, however, a new checking process is executed to determine whether there are new required crates available or not. If the answer is no, and there are still missing crates, this incomplete order could be sent to the waiting area for a specific time. This waiting time normally depends on the availability of required crates in the system, the priority of the customer, and the operating environment (see Figure 3.9).

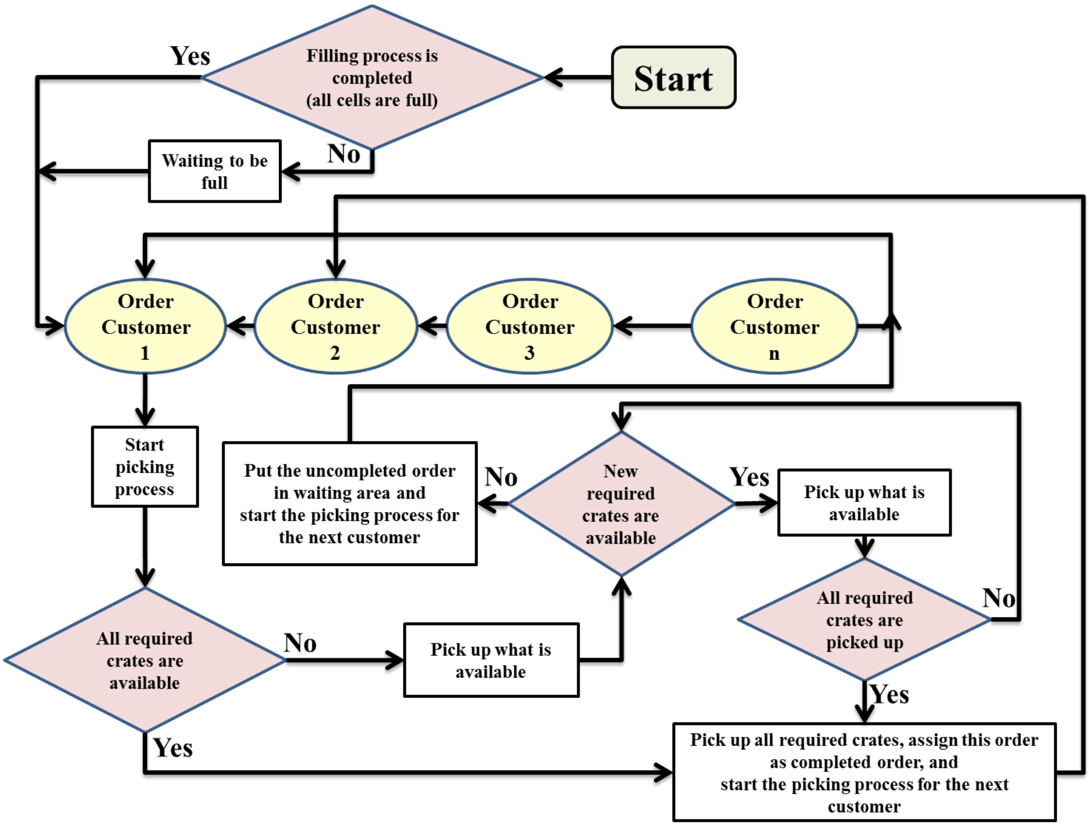


Figure 3.9 Flowchart of the first picking process scenario

- ***If the first cells (the nearest cells to the output point) were filled, picking process has started*** - the filling process starts in the first cells nearest to the outlets on the main conveyors. If these cells became full, the picking process can begin. The available required crates from these cells are immediately picked up. After every picking process, a checking process is executed in order to determine whether the new required crates are available. If there is no new availability of the required crates, the picking process for the next customer can begin. If the OPP for a customer is not completed in one stage, this customer would be put in a waiting area for a specific time in order to await new availability of their required crates. How often the customer is put in the waiting area depends on the availability of the required crates, the priority of this customer, and the operating environment. Sometimes the customer has to wait a full cycle until all customers are served in the first cycle, in order to be served again in a new cycle (see Figure 3.10).

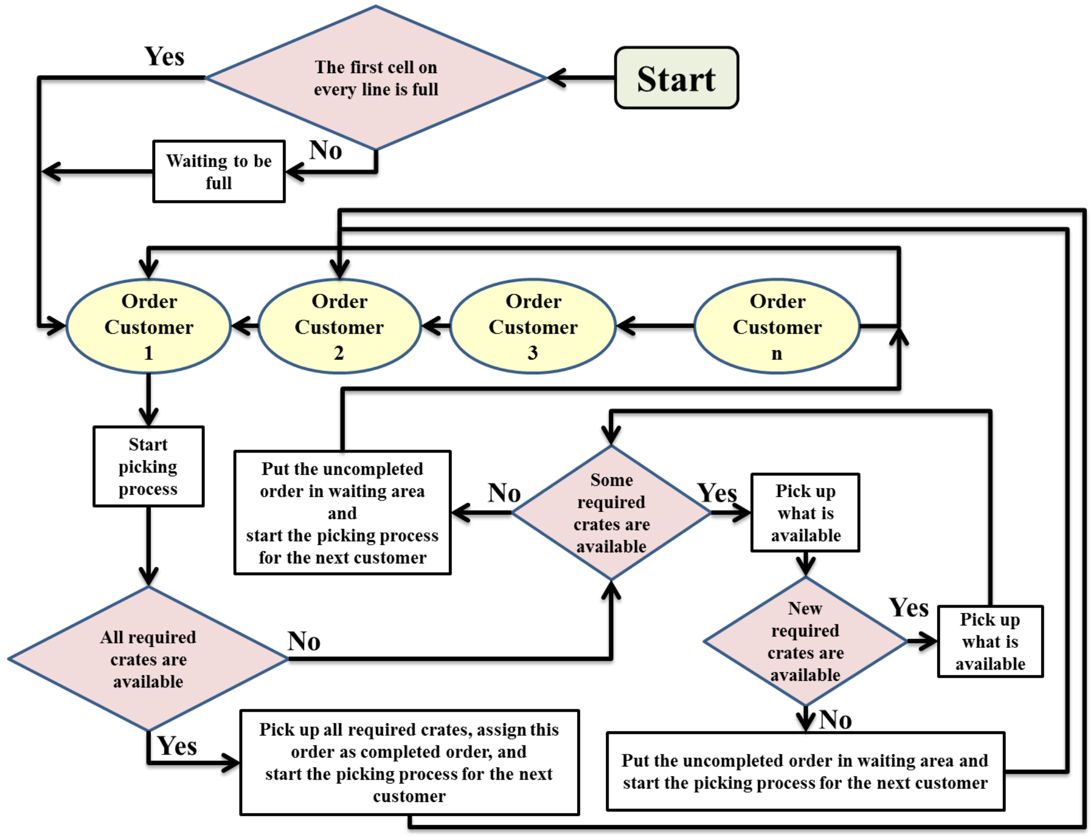


Figure 3.10 Flowchart of the second picking process scenario

If the first cells become full, the filling process is translated to the next cells. Every new full cell can be immediately considered in the picking process. The process continues until it reaches the last cell on every conveyor. Now, there are two possibilities: either a continuous replenishment process for every new empty cell is executed, and at the same time a continuous picking process is executed, or the replenishment processes are blocked and the picking processes are continued until the cells became empty, then a new filling cycle can be started to satisfy all customer orders and so on, until all customer orders are fulfilled. Organizing and controlling the picking and the replenishment processes and at the same time tracing and following-up the customers is a very complex process, which requires a very effective management and control system.

3.4.3 Replenishment process

The replenishment process is a very important process, because it is linked directly to the total time and cost of the OPP. Some systems, such as the A-Frame picking system, have a very high picking throughput, but the throughput of the replenishment process (manual) is very low compared to the picking throughput. As a result, the total throughputs of those systems are lower than expected and the total OP costs are increased. In other systems, the conflict between the picking process and replenishment process has the biggest effect on the total throughput of the system. In GRS there is a conflict between picking process and replenishment process. This means that is not possible to execute picking and replenishment at the same time. Either picking or replenishment can be executed at one time. An important advantage of the ACCPS is thus that the conflict between picking and replenishment can be minimized to zero. In order to reach zero conflict a special operating strategy is needed, which depends on the application area and controlling system performance. The replenishment and picking process conflicts in ACCPS can be discussed from many sides as follows

- ***Conflict of the replenishment process with the picking process for one cell:*** this happens if the replenished crates reach the cell at the same time as other crates leave the cell other crates leave this cell. The priority of processes must be explicit, because it is impossible to execute the two processes at the same time. One process must be stopped, until the other is completed. In this case, the picking process is given the highest priority, and the replenishment process must be blocked. If the type of the replenished crates is the same as the type of the required crates, the retrieval process of the cell is blocked and the required number of crates is fed directly from the replenished crates. The delay in this case is not really long, and its effect on the total OP time is limited. The most delay related to the replenishment process come from the different times between the instant of the replenishment recall and the instant of the arrival time, where the first replenished crate reaches the cell, and so to minimize this time, the expected required products are prepared and stored with the expected sequence very near to the input point of the ACCPS.
- ***Conflict of the replenishment process with the picking process for one line:*** if the replenishment and picking process take place at the same time for two different cells on the same line, two different situations can be analyzed based on the location of every cell on the conveyor. If the location of the cell that has a picking process is the nearest to the outlet of the main conveyor, there is no conflict between the replenishment and picking process. If the cell that has a replenishment process is the nearest, there is no potential to execute the two processes at the same time, and therefore one process must be blocked. Because the replenishment process usually takes longer time than picking process, it is blocked until the picking process is finished, and then the replenishment process can be released. Usually, the

replenishment batch size is one full pallet, but the volume of the required crates per article for a customer never reaches a full pallet.

- ***Conflict of the replenishment process with the picking process for the whole system:*** if the replenishment and picking processes are executed for two different lines at the same time, there is no problem and no delay time. There is no real conflict between the two processes, because every process is executed on a different line. There is thus no problem operating the picking process for two customers at the same time, but the picking process for the second customer can only be executed from the lines that have no required crates for the first customer. The picked stacks for the second customer are only conveyed to the accumulation collecting conveyor if all picked stacks for first customer have left the merge area (this area represents the area of all junction points between main conveyor and collecting conveyor) on this conveyor. That means that the idle lines can always prepare the required crates for the next customer. These prepared crates stay in the area between the stacking machine and the collecting conveyor, until the first customer leaves the merge area on the collecting conveyor. If the last picked stack for a customer has left the merge area, then the picking process for this customer is considered complete (the customer has left the system).

3.5 Management and Control Systems

Warehouse management involves the regulation and optimization of intricate warehouse operating and distribution strategies. WMS aims to optimize and control flows of material within the system. The concept of WMS thus goes beyond the scope of inventory management systems, which mainly focus on the interrelationships between amounts of items and storage spaces or places (Tompkins and Smith, 1998). WCS assists WMS, and can provide real-time directions for devices and controllers to fulfill orders quickly and accurately. The main objective of the WCS is to coordinate and control the devices or equipment in real-time, exchange the information with WMS, and ultimately achieve the goal of highly efficient and accurate flow of goods and information within the warehouse.

3.5.1 Management system

The management of warehouse operations has always been challenging for any warehouse. These challenges may concern storage, retrieval, supplier information, customer satisfaction, order management and delivery on time. Due to limitations of the available resources, equipment, staff, and space need to be selected cost effectively and precisely. Warehouses thus need an efficient WMS according to these requirements. To face these challenges and to survive in business competition, two main elements are very important, *"flexibility"* and *"adaptability"*. This means that the vendor should respond to customer demand in the minimum time and that the customer can demand changes. The company should provide the best service to the customer. Accurate and timely delivery are the key challenges in warehousing, however, a manual WMS cannot provide accuracy and punctuality due to the enormous workload caused by the paperwork required for more workers. To solve these problems, companies try to use computerized WMS, which have been developed with advanced technologies. The execution of warehouse operations depends on real-time data which is really difficult to handle in a manual system. Advanced information technologies offer new functionalities for the use of real-time data. For example, *"auto-ID"* and *"wireless sensor network technology"* work through radio frequency. These technologies provide accuracy by recording real-time data through scanners and sending this data directly to the server database. A warehouse needs a fast decision-making tool based on real-time data in order to manage all warehouse activities, which are continually changed. To optimize the management process, companies focus on the development of *"decision support models"* using mathematical techniques.

3.5.2 Control system

WCS is responsible for assigning location, shelf, and sub-shelf, and for the management of the order process. The WCS provides control of the operational equipment within the warehouse and gives an overall view of performance through a central observing point. The WCS also creates the connectivity of the software components such as the planning module for the WMS. It also controls the material handling operation and order management through PLC and/or PC-based cell controllers. The implementation of a WCS can be more efficient and convenient regarding cost than upgrading the current OPS. The basic objectives of WCS, according to Tompkins and Smith (1998), are: to identify and coordinate the work, to help maximize performance and customer satisfaction, to minimize mistakes, and to report the past, present and future work status via activity-based costing module. To manage all warehouse operations, the WMS and WCS work together as a one unit warehouse management and control system (WMCS). Warehouse management software manages the activities using data such as the warehouse in-out on schedule time, material movement, handling of goods, storage space information, staff reduction, wastage control, and performance monitoring, by using different modules. WCS is also a part of the software, and the user can control operational activities as well, such as loading, unloading, item-picking, etc. (Hompel and Schmidt, 2006).

All activities within ACCPS are automatically executed and controlled. According to the customer orders, the WMCS identifies the number of required pallets and sequences of these pallets that must be fed to the ACCPS. At the same time, the WMCS determines the location of every article in the ACCPS and takes responsibility for the execution, management and control of all OPP activities. Several operating modes could be applied and programmed depending upon the WMCS and PLC of the ACCPS as follows

- *Filling mode*: to fill all cells with the products
- *OP mode*: according to this mode, many scenarios could be applied to satisfy all operating strategies (see Section 3.4.2)
- *Replenishment mode*: preparing the pallets for the replenishment process in the best sequence according to the time of need
- *Emergency mode*: the WMCS is adapted to work under emergency case conditions, such as technical problems in one cell, in one line or others.

4 USE-CASE MODEL DESIGN AND TECHNICAL PARAMETERS

In this chapter an ACCPS use-case model is designed, and the layout of this use-case model is identified. The technical parameters of all components of the use-case model are determined. The most important calculations such as required area, space, times and costs are executed. A mathematical model is created to estimate the expected average throughput of the use-case model.

4.1 Introduction

In order to design and evaluate an OPS, especially in the early design phase, an analytical approach has to be used for a quantitative and qualitative description of the performance of every part in the system. Analytical models are generally design-oriented and can be used to rapidly find many alternative solutions. Other common approaches have been found by using simulation models, especially in the detailed design performance evaluation, however, this simulation approach is not applicable at very preliminary stages as it takes a long time to create and execute. At the same time, the cost is generally higher if there are too many scenarios and procedures that must be evaluated. In other words, analytical models are the best approach, and much cheaper. Analytical models deliver faster with more flexible solutions.

The analytical approach is thus used to analyze and design all system parts, which serve as assumptions for the mathematical tractability that may capture all details regarding system design. Similarly, an analytical model is built based on the main idea so as to evaluate the performance of the ACCPS, and to generate the mathematical model. In the next sections the analytical design procedures of the ACCPS use-case model are discussed in detail and executed for all parts of the use-case model.

4.2 Initial Technical Parameters of the ACCPS Use-Case Model

The flexibility of the system is very high as regard the ACCPS use-case model size. It is possible to build many use-case models with any number of cells on one conveyor, and with any number of conveyors, to form the whole use-case model. This depends on the requirements of the application area and the abilities of the resources, however, the main goal of logistics engineering is still to find the best solutions with the available resources. Depending on the requirements of an application area and the logistics engineering goals, the technical parameters of the ACCPS use-case model are assumed as follows

- The total number of the handled products is under one thousand
- The total number of the ordered SKUs per order-line is less than a pallet, because usually, when the number of the ordered SKUs per order-line is more than a pallet, it is more efficient to design a pallet pick than case pick process
- The minimum number of the ordered SKU per order-line is one unit
- 100 cells are assumed to be the total number of cells forming the use-case model, and these cells are divided by ten lines (10 main conveyors)
- The standard dimensions of the crate used in designing the use-case model, is the 34 liter Euro stacking container of 600 x 400 x 175mm. This type of crate can be stacked, and four stacks can be aggregated per Euro-pallet base (see Table 4.1)

Table 4.1 Technical specifications of the standard used crate (Schoeller Allibert, 2015)

Technical specifications	
Length:	600 mm
Width:	400 mm
Height:	175 mm
Max. load	20 kg
Max. static stacking load:	700 kg
Units/Euro-pallet:	52

- The standard height of the full Euro-pallet is 2.1m
- There are 13 crates per stack and 52 crates per pallet
- Only one type of product can be stored in the cell at one time
- The capacity of every storage cell is determined as 52 crates per cell.

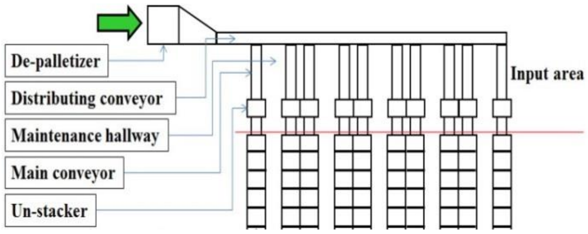
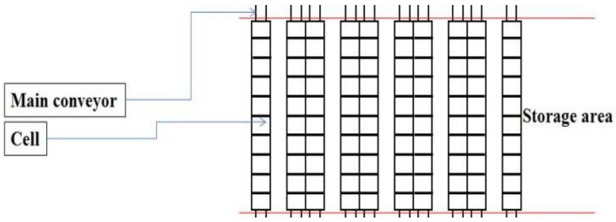
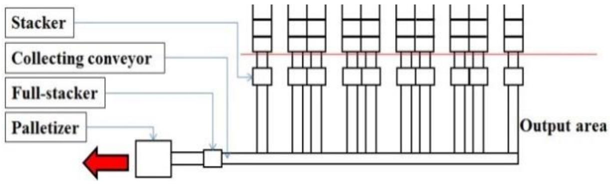
4.3 Size of the Applied ACCPS Use-Case Model

The use-case model size depends on many factors, such as number of cells, number of lines, the capacity of one cell, SKU profiles, application area, and capacities of resources. The ACCPS use-case model can be divided into three main areas: the input area, storage area and output area. Many factors have an influence on the design process of each area, but these factors must be integrated in a single design process to create the final layout of the use-case model. In some cases, the input area can be designed without the de-palletizing and the de-stacking machines, such as when the incoming goods to the ACCPS not in the form of pallets, but in the form of cases, directly from the production line, or from many feeding points. Otherwise, many de-palletizing robots can be used to split pallets directly into cases for dispensing the de-stacking machines.

The storage area can be designed and adapted according to the building structure, SKU profiles, and the required throughputs. According to the building structure, the cell heights may be compatible with the building’s height. A different number of cells can be installed from line to line to be compatible with the building’s area structure. Under specific conditions, the design of the output area can be changed. When the require area of the manual palletizing process is available, the output area can be designed without the stacking and the palletizing machines. That means the picked crates are directly transported to the customer’s pallet location (every customer has a specific pallet location in the picking area).

Actually, in order to reach the expected performance of the use-case model, some technical parameters could be changed in order to adapt the ACCPS structure with the new operating conditions in the application area. According to the all previous suggestions and described conditions, the use-case model size is specified in Table 4.2, where the use-case model is divided into three main areas. The input area contains the de-palletizer, distributing conveyor and the de-stackers, in addition to part of the main conveyors. The storage area contains the storage cells and the main parts of the main conveyors. The output area contains the stackers, collecting conveyor, full-stacker and the palletizer, in addition to a part of the main conveyors. The maintenance hallways extend to the three main areas to reach all parts of the use-case model. In order to reach the requested throughput according to the application area parameters, all parts that are located in the output area could be redesigned.

Table 4.2 The main parts of the ACCPS use-case model

Element	Main Parts (units)	Layout
Input Area	De-palletizing machines = 1 Distributing conveyors = 1 Main conveyors = 10 De-stacking machines = 10 Maintenance hallway = 5	
Storage Area	Main conveyors = 10 Storage cells = 100 Maintenance hallway = 5	
Output Area	Stacking machines = 10 Main conveyors = 10 Collecting conveyors = 1 Full-stacking machine = 1 Palletizing machine =1 Maintenance hallway = 5	

Changing the design of the output area is related directly to the physical shape of SKUs, the type of packaging, area availability, and the maximum required throughput. Similarly, the input area structure could be redesigned according to the application area and the location of the ACCPS within the warehouse or the DC in the supply chain. That means that the input area of the ACCPS could be designed without a de-palletizer if the ACCPS was located directly after a production area, where the product crates are directly fed to the ACCPS, however, the main structure of the storage area has more stability in its design than the others areas, and it is therefore not necessary to redesign the storage area according to the application area because it is the core of the ACCPS idea. Some small changes might be required, such as the dimensions of the cell or the use-case model, in order to be compatible with the SKUs and the application area.

4.4 General Layout of The ACCPS Use-case Model

The general layout of the use-case model depends on the location of every part, the connections between them, and the dimensions of each one. Two general layouts for the location of the input point and the output point can be found. The first is the *U-shaped flow*, which is used when the input and the output points are located on the same side. The second is the *I-shaped flow*, which is used when these two points not at the same side. See Figure 4.1.

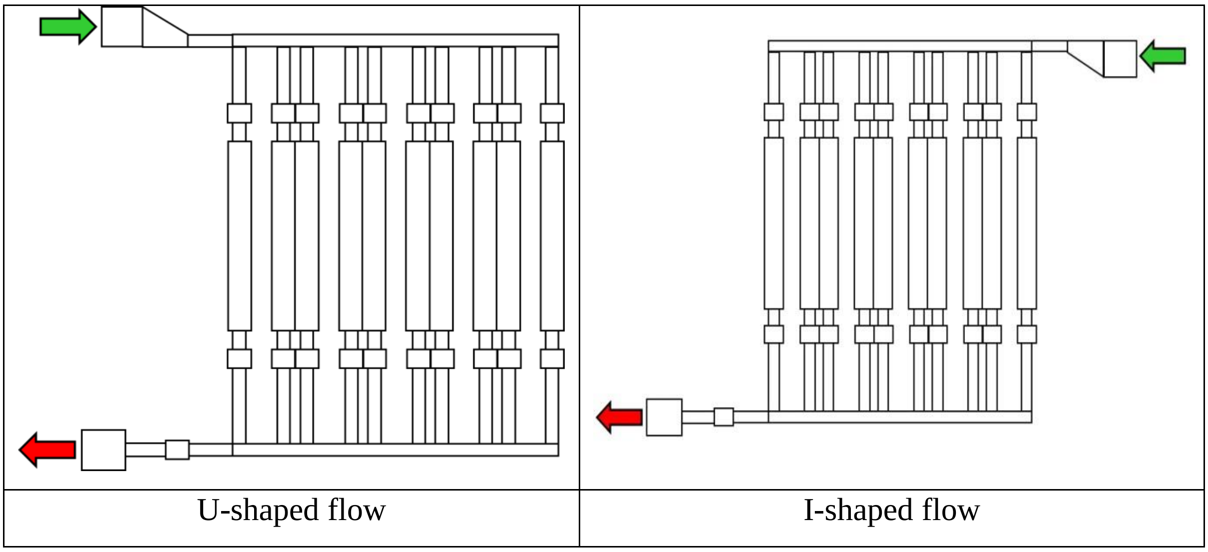
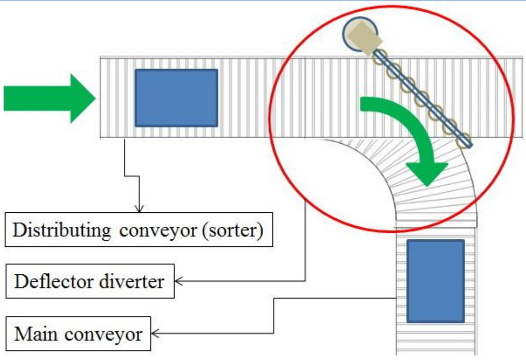
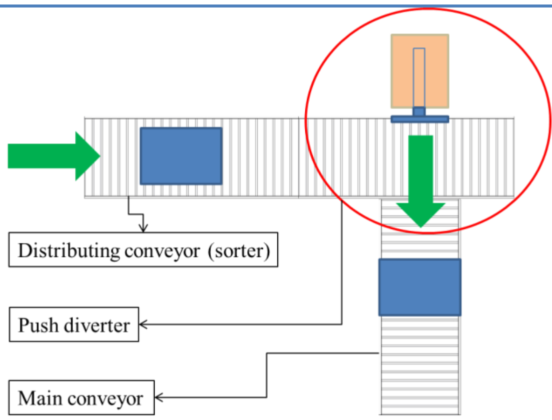
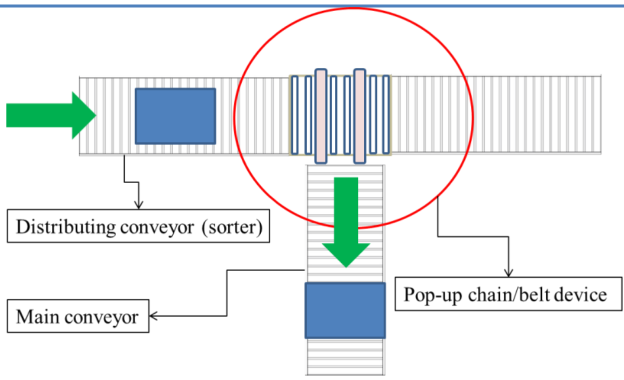
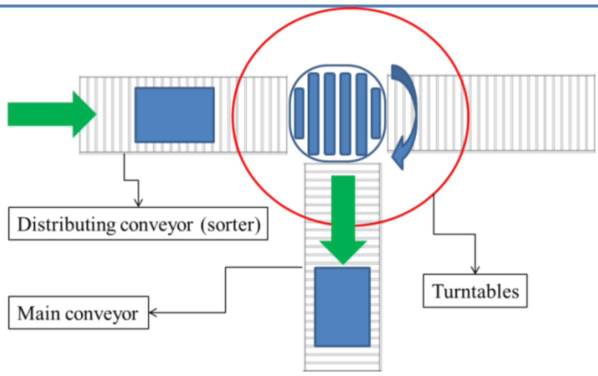


Figure 4.1 General layouts of ACCPS use-case model according to material shape flow

According to Kay (2012), a sorting system is composed of three subsystems: the ***merge subsystem, induct subsystem*** *and* ***sort subsystem***. Induct subsystems are used to identify the products and control the flow of the junction points. According to the mechanisms (diverters) of these junction points, the general layout of the use-case model could be changed. Diverters can be defined as stationary or movable arms that deflect, push, or pull a product to the desired destination.

Several types of diverters can be used within the use-case model to change the material's flow direction, especially at the connection points between the distributing conveyor (sorter) and the main conveyors from one side and between the main conveyors, and the collecting conveyor at the other side. There are many diverter mechanisms and principles, not all compatible with ACCPS, but the best one must be selected that be suitable for diversion the stacks and the crates in the same of operating speed. Table 4.3 illustrates the most common diverter mechanisms and principles for crates (see Table 4.3).

Table 4.3 Diverter principles can be used for ACCPS

Type	Layout
Deflector diverter **(Stationary or movable)**	
Push diverter	
Pop-up device **(Chain or belt)**	
Turntables	

Conveyor diverters can be selected depending on a wide variety of factors, including sorts per minute, space, package size and cost. The diverter principles which are compatible with this use-case model, and can be suitable to deal with stacks of crates, can be designed according to the junction form and the types of the conveyors used (see Figure 4.2a and 4.2b).

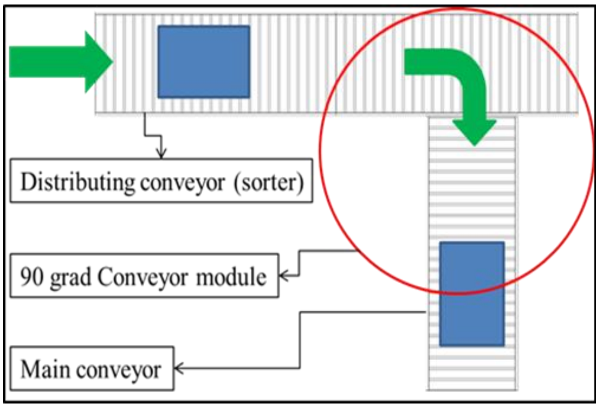


Figure 4.2a 90 grade conveyor transfer module

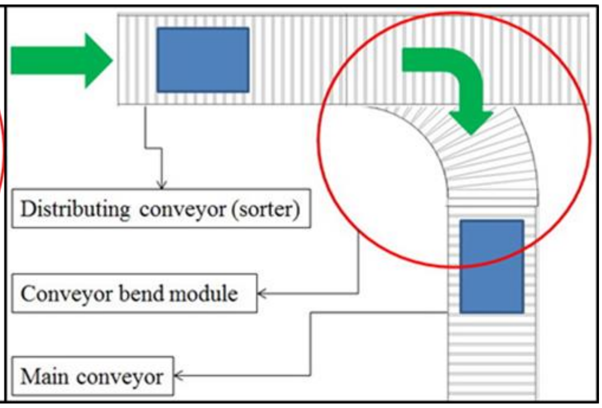


Figure 4.2b Curve conveyor transfer module

The stability of the moved stacks on the conveyors is very important, because it has a significant effect on the conveyors' applied speed. Stack stability plays a vital role in the selection process of the best transfer module between conveyors and the best diverter principle for the use-case model (see Figure 4.2a and 4.2b) and (Table 4.3). The technical reasons considered in selecting the best conveyor transfer module and diverter principle are:

- *Stability of the moved stacks*: when the crates or stacks are moved in the direction of the base length, they will be more stable compared to movement in the direction of the base width, and therefore, the direction of the crate flow must always be in the direction of the base length.
- *Smooth and continuous flow*: the flow of the stacks and crates must be continuous and smooth through their whole trip in the system, especially at the junction points, to avoid a blocked state in the system and any increase of trip time.
- *Standardizing conveying systems*: by using the same conveyor width and characteristics along the flow path of the stacks and the crates, the fixed costs of the system can be decreased.
- *Cell structure*: based on the crate base dimensions, two different types of crates (600x400mm and 400x300mm) can be handled by the cell without any change to the cell structure. The distances between the cantilevers of the elevation system are designed according to a common base dimension (400mm).

According to all previous technical parameters and suggestions, the final use-case model layout can be described as in Figure 4.3.

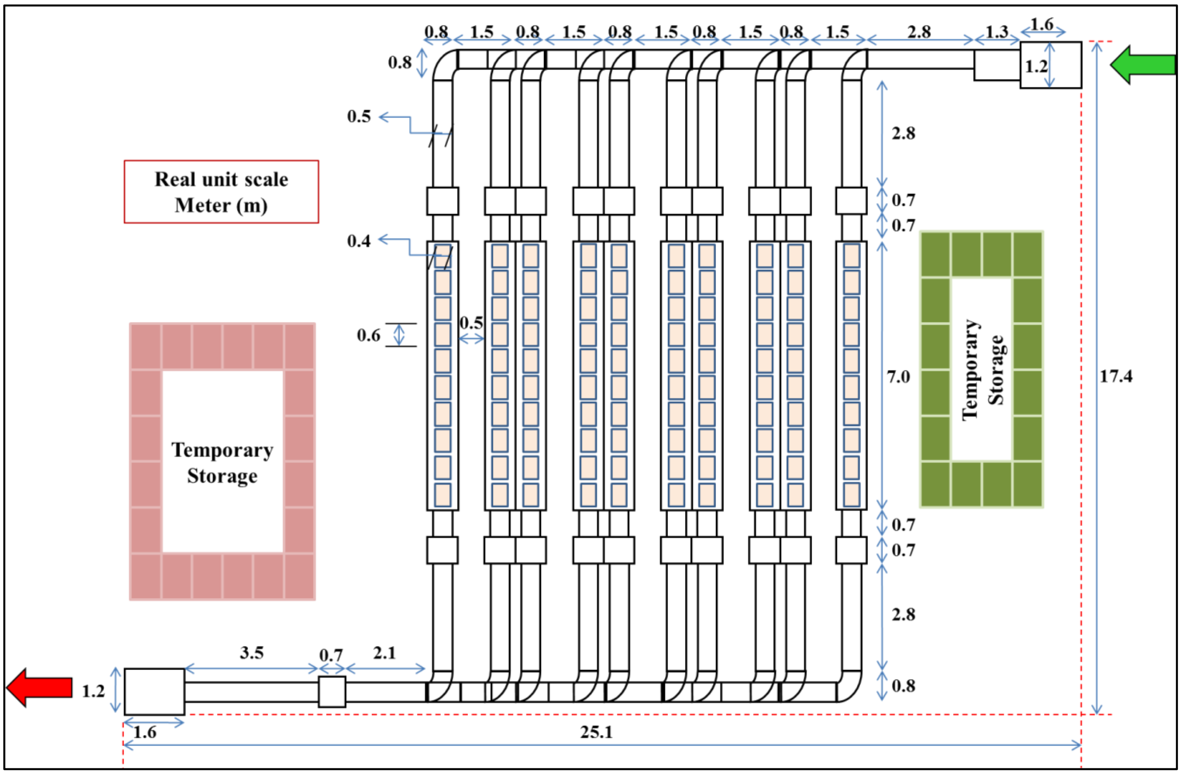


Figure 4.3 Final layout of the ACCPS use-case model

The locations of the de-palletizer and the palletizer could be changed to save more area, but these free areas could be used as temporary storage for the required pallets prepared with the required products, and for the incomplete customer orders.

4.5 Technical Parameters of the Use-Case Model's Parts

The basic parts of the ACCPS use-case model are the conveyor systems and the cells. The technical parameters of these two parts are important in determining the technical parameters of the other parts. According to Peters et al. (1998), the typical speed of a powered roller conveyor starts from 0.33m/s up to 1.27m/s depending on package sizes and weights. A horizontal conveyor speed of 0.5m/s is considered the standard speed of all conveyor systems in this use-case model. In reality, it is important to use a variable speed conveying system, but, the speed of 0.5m/s is considered an average conveying speed for the use-case model. In the same manner, the typical vertical speed of the elevator or the conveyor could be from 0.15m/s up to 0.3m/s. For this reason and according to the height of the storage position within the cell, the speed of the vertical elevation systems (cells) is selected as 0.25m/s for the standard vertical speed of the whole use-case model. In the next sections, the technical specifications of all parts of the system are determined, part by part.

4.5.1 Technical parameters of the storage cells

The structure of a storage cell involves four rectangular steel profiles, which are stabilized by cross links. The chains or belts of the cell's elevation system are tensed to two gear shafts, which are located on the upper and lower sides of the cell. A pair of chains or belts with hinged cantilever construction on each side gives the crates the required stability during all cell operation conditions. The vertical speed and the direction of rotation of all chains are controlled all the time to be synchronous by connecting two drive shafts. One of these drive shafts is directly connected to a motor on one side, and the other is connected to a second shaft on the other side of the cell. Each pair of chains has the same number of stages and the same distance between them. This distance comprises the height of the load carrier and the distance between the load and the next stage. The independent stages consist of plates which are connected to 90° hinges at two positions with chains. At the highest point of the chain, the hinge construction starts to close the cantilever form. This principle decreases the safety space between two cells, which are installed back to back in two different storage lines (the next conveyor can be positioned closer) (see Figure 4.4).

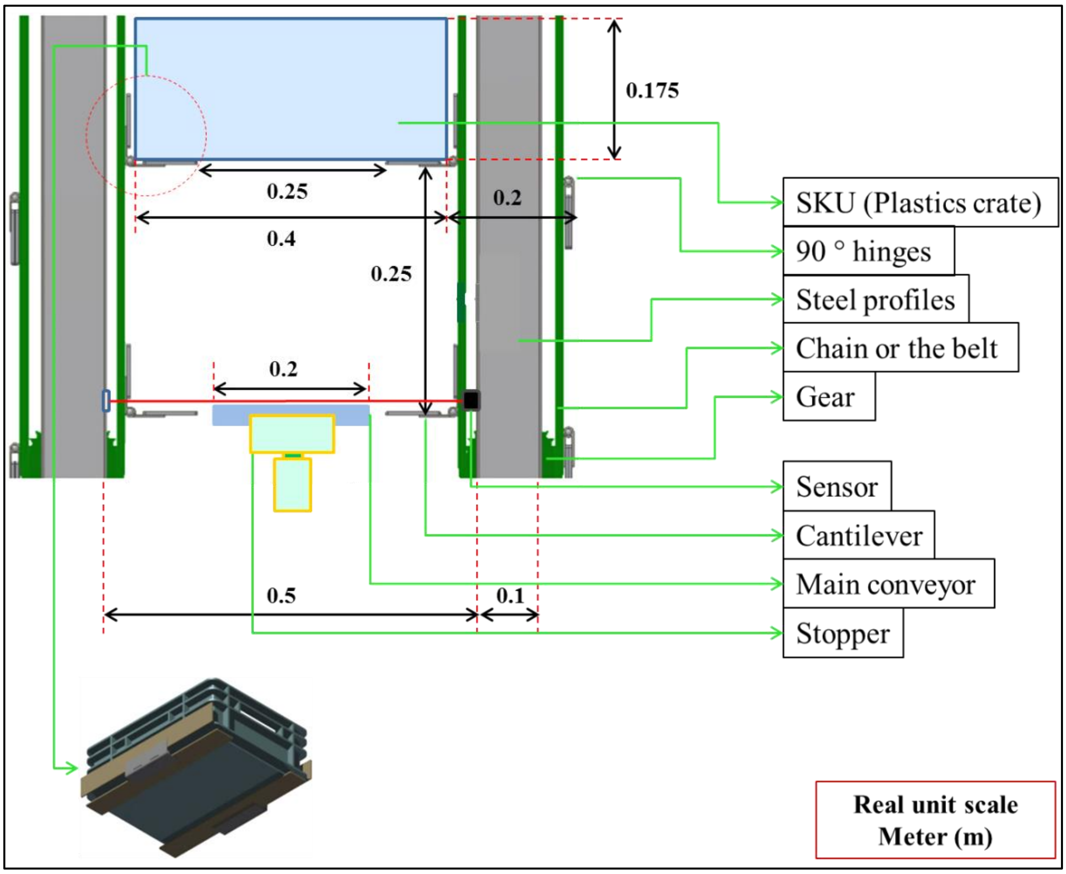


Figure 4.4 The front view of the cell structure and the main parts

Basically, the throughput of the use-case model depends on the throughput of the storage cell and total number of main conveyors within the use-case model. It is therefore, important to find the maximum throughputs of one cell in order to determine the maximum throughputs of the use-case model. All movements in the ACCPS use-case model are in the form of linear motion (horizontal motion on conveyors and vertical motion in cells), which means that it is very easy to calculate the traveling time of the crates in the use-case model when the displacements and velocities of these crates are determined. The horizontal and vertical crate velocities (0.5m/s and 0.25m/s) were already determined, as were the crates' vertical displacement (0.25m). That means it is necessary to calculate the horizontal displacements of the crates. The horizontal displacement of the crate when entering or leaving the cell is the same (0.7m), which is explained according to the construction detail of the storage cell that is illustrated in Figure 4.5a and b.

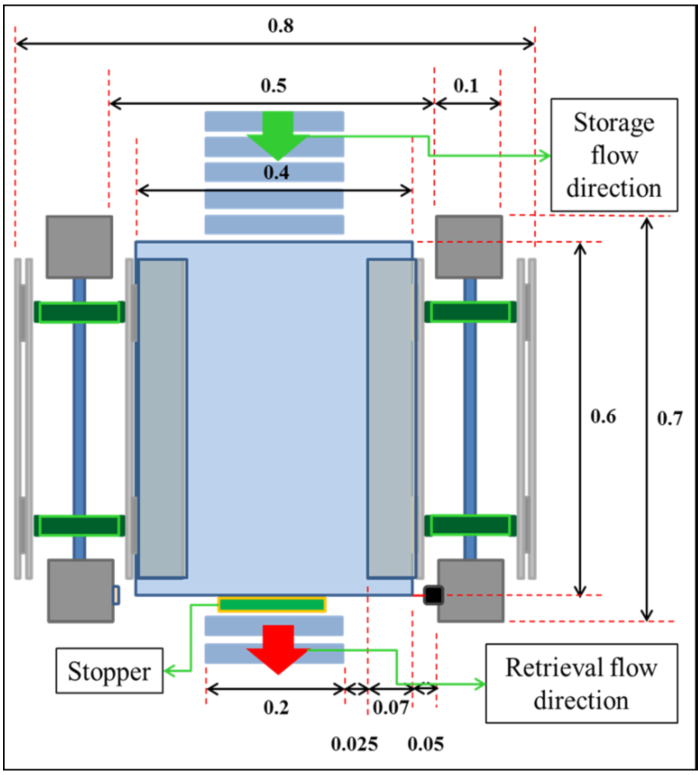


Figure 4.5a Top view of the one storage cell

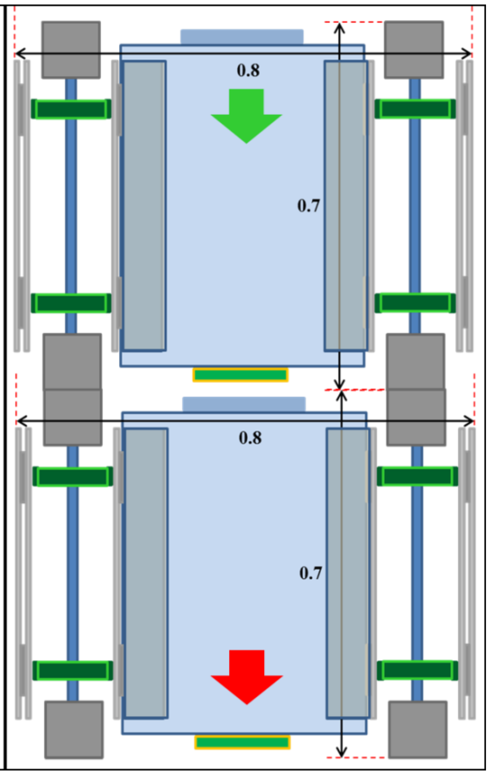


Figure 4.5b Top view of two storage cells

To determine the maximum throughput of one cell, some assumptions are kept in mind as follows

- The feeding flow of the crates is a continuous flow.
- The horizontal traveling time is only considered when the first crate is at the boundary of the cell.

For example, in Figure 4.6, crate_3 will enter cell_n, and the horizontal traveling time is only considered if it is at the boundary of cell_n-1. After 0.7 m horizontal traveling displacements, crate_3 will be in the heart of cell_n, and crate_4 will be at the previous location of crate_3. After this step, the stopper to cell_n-1 is activated to stop any flow in the direction of cell_n. At this point the elevation system of the cell number is activated and crate_3 is lifted to the position of crate_2, while crate numbers 2 and 1 are raised to reach the lifting displacement (0.25m). This process is continued until the number of stored crates in the cell reaches m, where m refers to the capacity of the cell (see Figure 4.6).

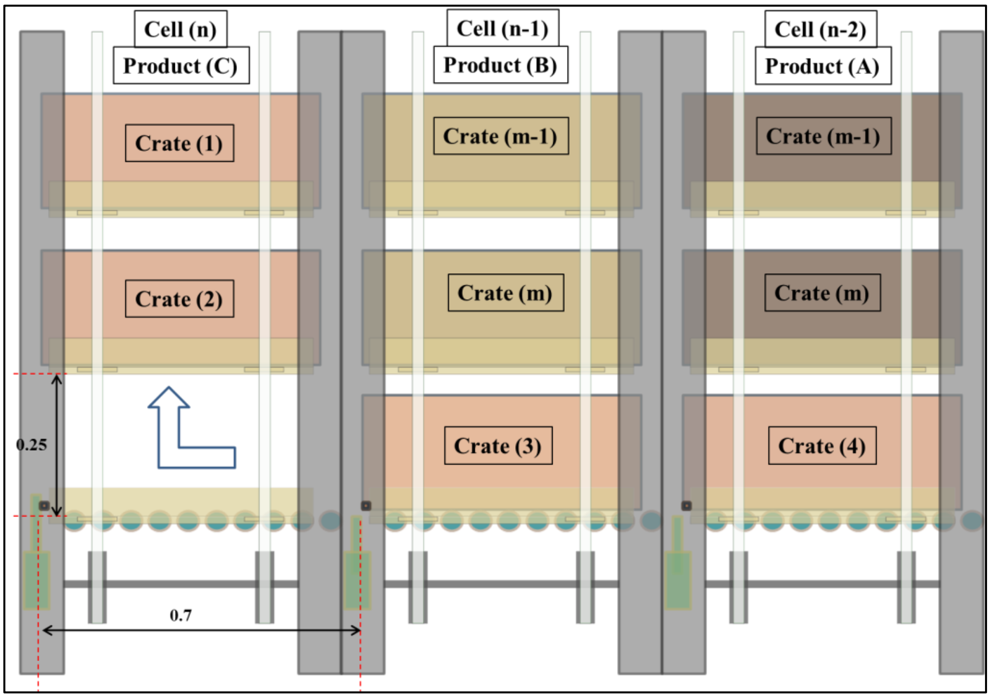


Figure 4.6 Side view of a storage line with three cells

During the retrieval processes, the same steps take place, but the flow direction is changed to be from the cell to the output point. The vertical and horizontal displacements are thus considered under the same condition. The throughput of the cell during the storing processes, or during the retrieving processes, is the same. To estimate the throughput of one cell per line, the total traveling time of the storage or the retrieval process of one crate must be determined. The next formula determines the total required time for a crate storage or retrieval process as follows

$$T_{crate}^{t} = t_h + t_v \,, \tag{4.1}$$

where

$$t_h = \frac{L}{v_h} = \frac{0.7}{0.5} = 1.4s \; and \;\; t_v = \frac{H}{v_v} = \frac{0.25}{0.25} = 1 \; s \,,$$

then

$$T_{crate}^{t} = t_h + t_v = 2.4\ s$$

where

- T_{crate}^{t}: the total traveling time of the crate during storage or retrieval process within the boundary of the cell
- t_h: horizontal traveling time of the crate on the main conveyor
- t_v: vertical traveling time of crate in the cell
- L: horizontal crate displacement
- v_h: horizontal crate velocity
- H: vertical crate displacement
- v_v: vertical crate velocity.

The total traveling time of the crate during a storage or retrieval process is thus 2.4 seconds. It can be understood that there could be a storage or retrieval process for a crate into or from the cell every 2.4 seconds. This time represents a cycle time, and the throughput of the cell represents the number of cycles per hour. The maximum throughput of one cell per line is thus estimated as follows

$$Thr_{cell/line}^{max} = \frac{1h * 60 * 60}{T_{crate}^{t}}\ , \tag{4.2}$$

then

$$Thr_{cell/line}^{max} = \frac{1h * 60 * 60}{2.4} = 1500\ crates/h\ ,$$

where $Thr_{cell/line}^{max}$: maximum throughput of the cell per line.

To estimate the maximum throughput of the use-case model, the maximum throughput of the cell is multiplied with the number of the use-case model's storage lines. The maximum throughput of the use-case model is therefore estimated as follows

$$Thr_{model}^{max} = Thr_{cell/line}^{max} * Nr^{SL}\ , \tag{4.3}$$

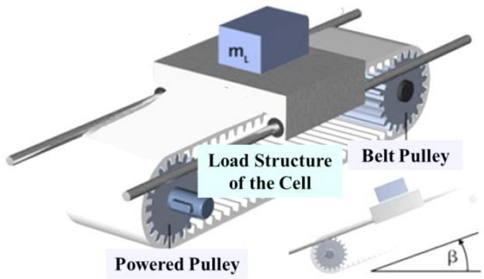
where Thr_{model}^{max} is the maximum throughput of the use-case model and Nr^{SL} is the number of the storage lines in the use-case model.

Then

$$Thr_{model}^{max} = 1500 * 10 = 15000\ crates/h\ .$$

The drive solution designer tool from the ***LENZE*** Company was used to design the drive system of the cell. The power of the cell's motor was selected according to the cell's elevation system structure, the total loads, and the kinematic behavior of the system. Table 4.4 illustrates the technical parameters of the storage cell and the input data for these factors.

Table 4.4 The input data of the cell's drive system design



Technical parameters of the cell's elevation system	
Powered and belt pulley diameters	150 mm
Mass of the slide (m_L)	1040 kg
Angle of tilt (β)	90.0 °
Transmission efficiency of toothed belt	0.970
Mass of toothed belts	160 kg
Vertical displacement	0.25 m
Traveling time	1 s

Based on these design conditions, the practical velocity of the cell's elevation system is determined as 0.375m/s and the acceleration as 1.12m/s^2. Figure 4.7 illustrates the kinematic behavior of storage or retrieval process of a crate within or from a cell.

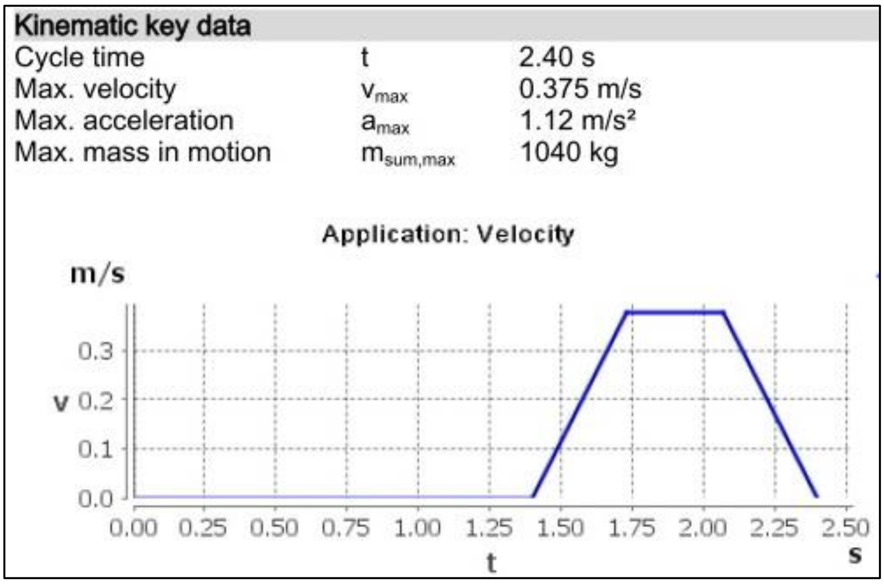


Figure 4.7 Kinematic specifications of the cell's elevation system

The power of the required motor has been determined as 4.47 kW and the energy consumption of one cycle as 1.3e-03 kWh per cycle. By using the drive solution designer tool from the *LENZE* Company, the technical specifications of all other parts of the cell's drive system could be directly determined.

Based on the assumption that there is no negative effect from the input area and output area on the maximum throughput of the use-case model, the technical parameters of all parts of these two areas would be designed based on the maximum throughput of the use-case model.

4.5.2 Technical parameters of the de-palletizing machine (de-palletizer)

The incoming pallets are fed to the de-palletizer by workers using forklifts, or automatically by an automated stacker crane. These pallets are then disassembled into stacks, which are moved to the distributing conveyor. It is therefore necessary to install a de-palletizer that is able to handle - at a minimum - the maximum throughput of the use-case model. That means this machine should have the capacity to disassemble a number of pallets with a number of crates that at least equals the maximum number of crates handled by the whole use-case model in one hour. To achieve this goal, the machine should work fast enough to disassemble the incoming Euro-pallets into four stacks. The disassembly process of the incoming pallets is divided into many interval times: ***input time***, for a pallet's entrance process in the de-palletizer; ***processing time***, for separating the stacks from the pallet's wood base, by lifting up the four stacks and then disposing of the empty pallets and at the end putting the stacks down on the main machine's conveyor; ***departing time***, for the four stacks to leave the boundary of the de-palletizing machine (see Figure 4.8).

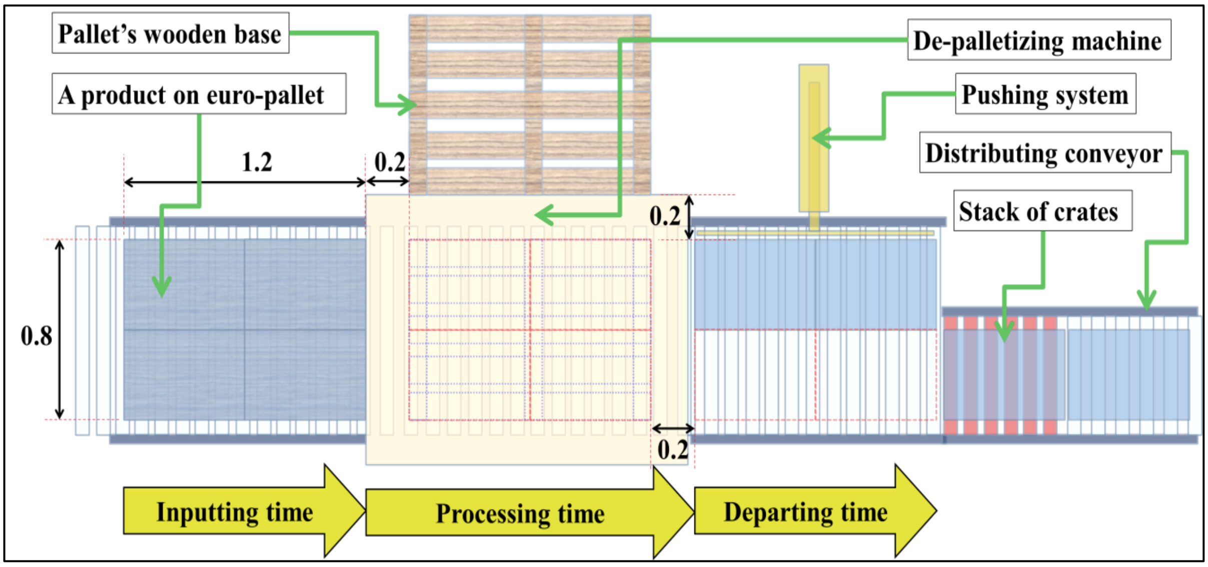


Figure 4.8 De-palletizing process for incoming pallets

The minimum throughput (the minimum disassembling rate (pallets per hour)) of the required de-palletizing machine is determined by dividing the maximum throughput of the use-case model by the total number of crates per pallet as follows

$$Thr_{dep}^{min.req} = \frac{Thr_{model}^{max}}{Nr.^{cr/pa}}, \tag{4.4}$$

then

$$Thr_{dep}^{min.req} = \frac{15000}{52} = 288.4\frac{pallets}{h},$$

and

$$T_{pa}^{ave.dep} = \frac{1h * 60 * 60}{Thr_{dep}^{min.req}} = \frac{1h * 60 * 60}{288.4} = 12.5\ s\ , \tag{4.5}$$

where $Thr_{dep}^{min.req}$ is the minimum required throughput of the de-palletizer, $Nr^{cr/pa}$ is the number of crates per pallet, $T_{pa}^{ave.dep}$ is the available de-palletizing time for a pallet.

For determining all interval times of the disassembly process, the horizontal speed of the feeding conveyor is taken as the use-case model's standard horizontal speed (0.5m/s). The input interval is calculated by determining the pallet's traveling displacement (1.4m as in Figure 4.8), dividing by the horizontal velocity of the de-palletizer conveying system as follows

$$T^{in} = T^{de} = \frac{D}{v_h} = \frac{1.4}{0.5} = 2.8\ s\ ,$$

where T^{in} is the time of the input interval for the pallet within the de-palletizer and T^{de} is the time of the departing interval for the pallet within the de-palletizer.

The processing time is calculated by determining the time of every step in this process. When the pallet inters the de-palletizer, the de-palletizer picks up all the stacks and lifts it up a little. The wooden base of the pallet leaves the de-palletizer, the stacks that are picked up and raised are moved down to place them on the de-palletizer conveyor, and then these stacks are released to depart the de-palletizer. This means that the processing time has five interval times, the pick time, lifting time, wooden base leaving time, taking down time and release time. All interval times can be taken as one second for every step, except the wooden base departing time which is calculated by dividing the traveling displacement (1m as in Figure 4.8) by the leaving velocity (suggested to be 0.5m/s) as follows

$$T_{w.b}^{de} = \frac{D^{de}}{V^{de}} = \frac{1}{0.5} = 2\ s\ ,$$

then

$$T^{pro} = 4 + 2 = 6\ s\ ,$$

where $T_{w.b}^{de}$ is the departing time of the wooden base within the de-palletizer, D^{de} is the departing displacement of the wooden base within the de-palletizer, V^{de} is the departing velocity of the wooden base within the de-palletizer, and T^{pro} is the processing time of the de-palletizing intervals within the de-palletizer.

The required time for de-palletizing a pallet ($T_{Pa}^{Req.Dep}$) then equals

$$T_{pa}^{req.dep} = 2.8 + 6 + 2.8 = 11.6\ s.$$

The calculated required time for de-palletizing one pallet (11.6s) is less than the available time (12.5s) for this step (11.6s<12.5s). According to this technical parameter, a standard de-palletizer could be used, which has a throughput of 288 pallets per hour. Several de-palletizing machines could be installed to stratify the required de-palletizing throughput based on the design of the ACCPS input area design and the throughput of the installed de-palletizer.

4.5.3 Technical parameters of the distributing conveyor

Based on the design of the ACCPS storage area, all stacks departed from the de-palletizer are fed into ten lines by a distributing conveyor. The throughput of the distributing conveyor must be at least the maximum throughput of the use-case model, which equals the throughput of the de-palletizer. As previously known, the maximum throughput of the use-case model equals to 15000 crates/h, the number of crates in one stack is 13 crates/stack, and the horizontal velocity of the distributing conveyor is 0.5m/s. According to these required technical parameters, the distributing conveyor is selected, where the required length is 14.3m with ten junction points for ten main conveyors, and every junction has a roller deflector diverter with a bend conveyor part (see Figure 4.9).

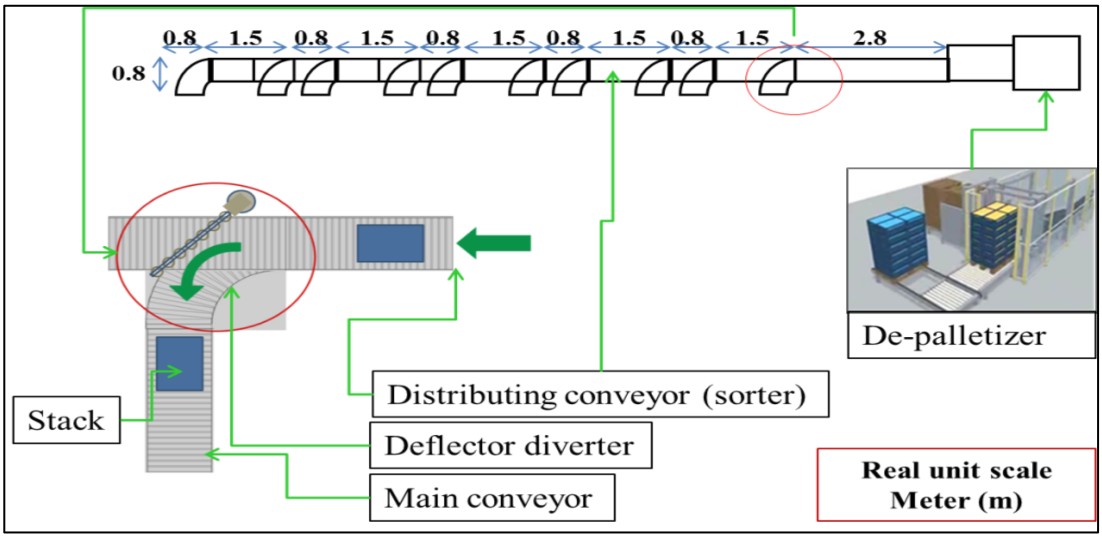


Figure 4.9 Distributing conveyor with roller deflector diverter

The required throughput of the distributing conveyor represents the total number of the stacks, which must be conveyed by the distributing conveyor to the main conveyors each hour. The minimum required throughput of the distribution conveyor is determined as follows

$$Thr_{dis.con}^{min.req} = \frac{Thr_{model}^{max}}{Nr^{\frac{cr}{st}}} , \tag{4.6}$$

then

$$Thr_{dis.con}^{min.req} = \frac{15000}{13} = 1154\ stacks/h ,$$

where $Thr_{dis.con}^{min.req}$ is the minimum required throughput of the distribution conveyor and $Nr^{cr/st}$ is the number of crates per full-stack within the pallet. This means that the distributing conveyor must have the ability to feed 1154 stacks per hour as the minimum. According to the suggested technical parameters of the distributing conveyor, the available throughput of the distribution conveyor is determined via the maximum number of stacks that this conveyor can feed per hour ($Thr_{dis.con}^{max}$). In order to determine the $Thr_{dis.con}^{max}$, the traveling time of a stack on this conveyor must be calculated by dividing the traveling displacement of one stack footprint by the velocity of the conveyor (0.5m/s). The maximum number of stacks that the distribution conveyor can feed per hour (maximum available throughput) is therefore calculated as follows

$$Thr_{dis.con}^{max} = \frac{1h}{T_{dis.con}^{st.tra}} , \tag{4.7}$$

and

$$T_{dis.con}^{st.tra} = \frac{D_{st}^{tra}}{v^{dis.con}} = \frac{0.6}{0.5} = 1.2\ s ,$$

where $Thr_{dis.con}^{max}$ is the maximum number of stacks that the distribution conveyor can feed per hour, $T_{dis.con}^{st.tra}$ is the raveling time of a stack on the distribution conveyor, D_{st}^{tra} is the traveling displacement of a stack on the distribution conveyor, and $v^{dis.con}$ is the velocity of the distributing conveyor. That means that every 1.2 seconds the distributing conveyor can feed a stack, and therefore, the available throughput of the distributing conveyor is calculated by dividing the seconds of an hour by the stack traveling time on the distributing conveyor as follows

$$Thr_{dis.con}^{max} = \frac{1h * 60 * 60}{1.2} = 3000\ stacks/h .$$

The maximum available throughput is thus more than that required at a velocity of 0.5m/s, and there is therefore a potential for decreasing the velocity of the distributing conveyor. By checking the throughput of the distributing conveyor, it was found that by decreasing the distributing conveyor's velocity to half, the available throughput was still higher than that required.

4.5.4 Technical parameters of the de-stacking machine

The stacks that are fed from the distributing conveyor must be split into crates, before they enter the storage area on the main conveyors. A de-stacker is installed on each storage line at the beginning part of the main conveyor. The footprint of the de-stacker in the flow direction of the material is 0.7m (see Figure 4.10).

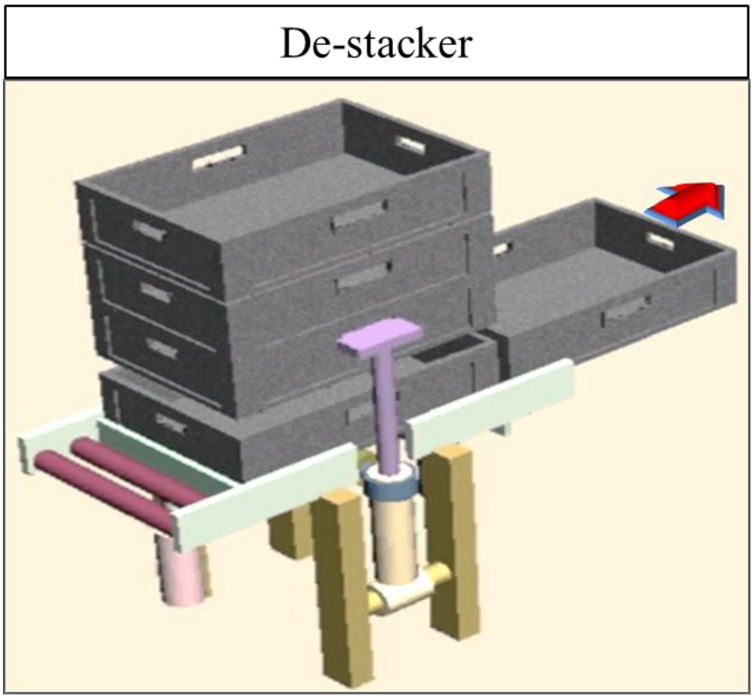


Figure 4.10 De-stacking machine

The minimum required throughput of the de-stacking machine must be at least equal to the maximum throughput of one main conveyor. That means a standard crate de-stacker could be used, but its throughput must not be lower than 1500 crates per hour. The de-stacking process is designed to take no more than 2.4 seconds per crate. In order to avoid blocking in the material flow within the system, the time for the de-stacking process is designed based on the storage process time for a crate within the cell. De-stackers that can handle two stacks at once could therefore be used if it is necessary.

4.5.5 Technical parameters of the main conveyor

The main conveyor consists of three parts. The ***first part,*** the buffering conveyor before the de-stacking machine, is designed to handle stacks of crates. The capacity of this part is designed as four stacks, and the total length is designed based on crate flow direction according to the base dimension of the handled crates. The total length is therefore 2.8m. The ***second part*** extends from the de-stacking machine to the stacking machine. This part extends under all the cells installed on this storage line and the paths through all these cells, which are located on this main conveyor. This part is designed to handle single crates and not stacks of crates. The length of this part is 8.4m. Ten cells are installed on this part, where the total length is 7m, and the rest is divided into two parts (0.7m) directly after the de-stacker and before the stacker. A crate stopper mechanism is installed for every cell, this stopper can be a pneumatic cylinder or an electrical solenoid mechanism. This stopper has two main tasks; the first is to stop the incoming crates in the boundary of the cells, where the crates must be on the right place under the cell in order to lift it and store within this cell, and the second is to stop the other crates colliding with the crate that has entered or is leaving the cell. The ***third part*** of the buffer conveyor is designed for accumulation stacks of crates after the stacking machine. This part is designed to contain four stacks at once, and its length is 2.8m (see Figure 4.11).

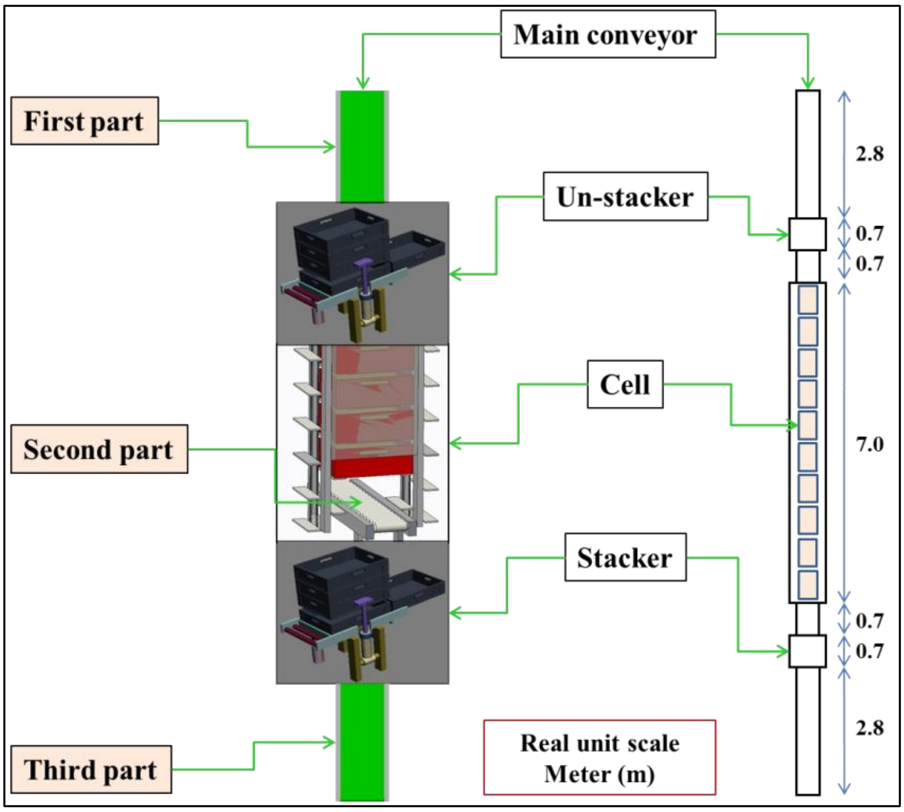


Figure 4.11 Layout of the main conveyor and its parts

The average velocity of these parts is designed to be the same as a standard conveyor's velocity 0.5m/s. Many conveyor types and stopper systems could be used to handle crates. Selection the best one depends on the cost and robustness of these systems, and therefore the roller conveyor type was selected for all convoying parts in the ACCPS use-case model.

4.5.6 Technical parameters of the stacking machine

The retrieved crates taken from the cells to satisfy a customer order are restacked before they are moved from the main conveyors to the collecting conveyor. The crate stacking machine is installed at the end of the second part of the main conveyor, which is the end boundary of the ACCPS storage area. The minimum required throughput of the crate stacker must be at least the same as the maximum throughput of one main conveyor (1500crates/h), and therefore the stacking process is designed to take only 2.4 seconds per crate. The stacking process is designed to stack 13 crates in one full-stack (see Figure 4.12).

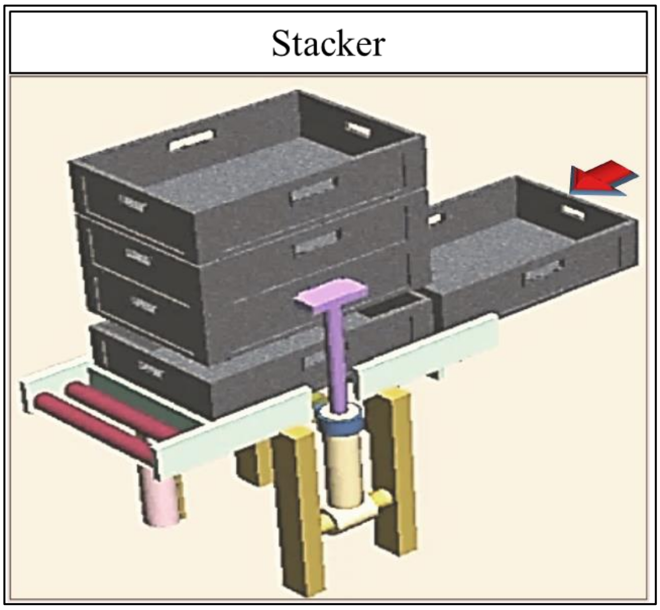


Figure 4.12 Stacking machine

The full-stacks are the stacks that emerge from the stackers with a full number of crates, the full number of crates is based on the total number of crates per retrieved pallet. In this use-case model, the full-stack has 13 crates per stack, but, there is the potential that partial stacks (small-stacks) will emerge from the stackers. Small-stacks form if the number of retrieved crates from a storage line not reaches the total number of crates in a full-stack (13 crates), or if the last retrieved crates from the storage line of an order picking process for one customer are not enough to form a full-stack. Many small-stacks could thus come from the stackers for one customer. The small-stack form is undesirable because it increases the total number of pallets delivered per customer. In order to minimize the total number of pallets delivered per customer by minimizing the total small-stacks, a full-stacker (re-stacker) is installed at the end of the collecting conveyor before the palletizing machine at the end of the ACCPS.

4.5.7 Technical parameters of the collecting conveyor

The collecting and distributing conveyors are of the same design and the same technical parameters, but, the task of the collecting conveyor is to aggregate the picked stacks from all main conveyors and to transport them - at the end - to the palletizing machine (palletizer). The average transport velocity of this conveyor is 0.5 m/s. The required throughput of this part must be not lower than the throughput of the use-case model, where the maximum throughput of the use-case model is 1154 stacks/h. That means the collecting conveyor must have the minimum ability to transport 1154 stacks per hour. The required length of the collecting conveyor is 13.9 m. There are ten junction points for ten main conveyors, and every junction has a roller deflector diverter with a bend conveyor part (see Figure 4.13).

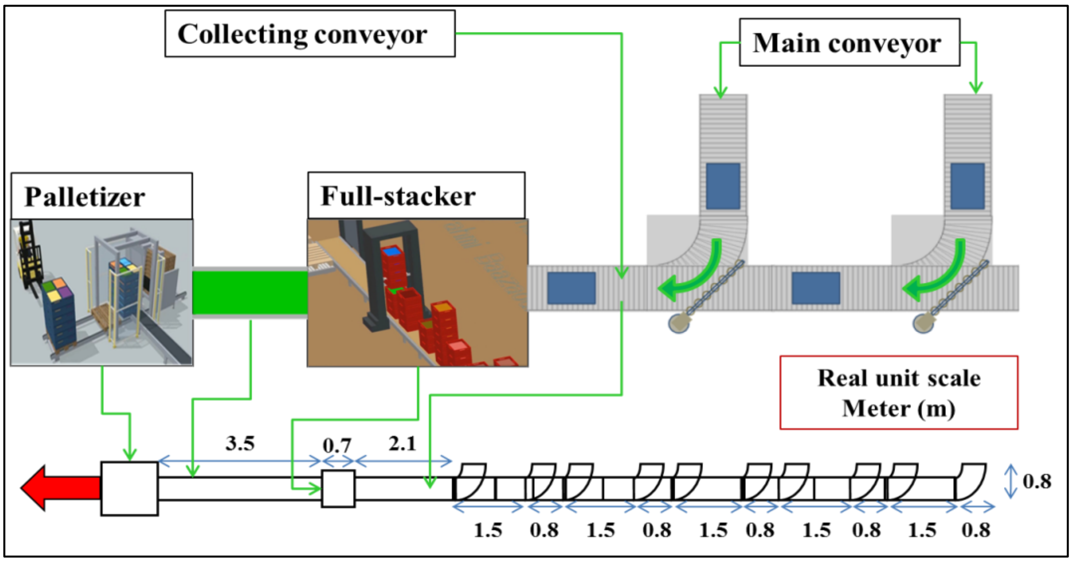


Figure 4.13 Layout of collecting conveyor and its parts

The available throughput of the collecting conveyor is determined based on its technical parameters. The traveling time of a stack on this conveyor is calculated by dividing the traveling displacement (0.6m) - which is the footprint of a stack - by the velocity of this conveyor (0.5m/s) as follows

$$T_{col.con}^{st.tra} = \frac{D_{st}^{tra}}{v^{col.con}} = \frac{0.6}{0.5} = 1.2\ s\,,$$

where $T_{col.con}^{st.tra}$ is the traveling time of a stack on the collecting conveyor and $v^{col.con}$ is the velocity of the collecting conveyor. This means that the collecting conveyor can feed a stack every 1.2 seconds, and therefore, the maximum available throughput of the collecting conveyor is calculated by dividing the seconds of an hour by the stack traveling time on the collecting conveyor as follows

$$Thr_{col.con}^{max} = \frac{1h * 60 * 60}{1.2} = 3000\ stacks/h\,.$$

The maximum available throughput is thus more than that required at a velocity of 0.5 m/s, and therefore, the velocity of the collecting conveyor could be decreased, but in the reality, the traveling time of a stack on the collecting conveyor takes longer than expected, because of the gap between the transported stacks over the conveyor, as for the distributing conveyor. The average traveling displacement of a stack over the collecting and distributing conveyors will thus be the footprint of a stack plus the expected average gap between two transported stacks over these conveyors.

4.5.8 Technical parameters of the full-stacking machine (re-stacker)

In this use-case model, any output stack that contains less than 13 crates is defined as a non-full-stack (small-stack). A full-stack is any stack that contains 13 crates. Sometimes the main conveyors feed the collecting conveyor with many small-stacks. These small-stacks must be aggregated to form full-stacks in order to minimize the total delivered pallets and trucks per customer. A re-stacking station to handle the stacks (also known as a full-stacker) is thus installed on the end of the collecting conveyor. The small-stacks that are delivered from the collecting conveyor will be re-stacked into full-stacks. The height of the delivered stacks or pallets is an adjustable height, so all four stacks that belong to one pallet can be the same height.

The full-stacker is equipped with sensors to detect the height of each stack or the number of crates per stack. When a small-stack is detected, an examination process is automatically executed to determine whether it is the last stack of an order or not. If the answer to this query is yes, the small-stack is transported directly to the next station (palletizer), and if the answer is no, the small-stack is taken up by the full-stacker, and the full-stacker aggregates it with the next small-stack in the same order. If the newly formed stack is still in the form of a small-stack, the machine takes it up and waits to aggregate it with the next small-stack. If there are more than 13 crates with small-stacks, the full-stacker builds and releases a new full-stack with 13 crates, and the rest it takes it up.

An examination process always is executed to determine the last stack in the picking process of an order. If the rest of the crates are determined as the last stack of the order, the full-stacker releases them in order to transport the stack directly to the palletizer. If a new full-stack is formed by the full-stacker, the full stacker always releases it directly in the direction of the palletizer, and an examination process is executed to determine the last stack of the order. Figure 4.14 is a flowchart of the working logic of the full-stacker, and the full-stacker machine and its operating principles are designed according to this working logic (see Figure 4.14).

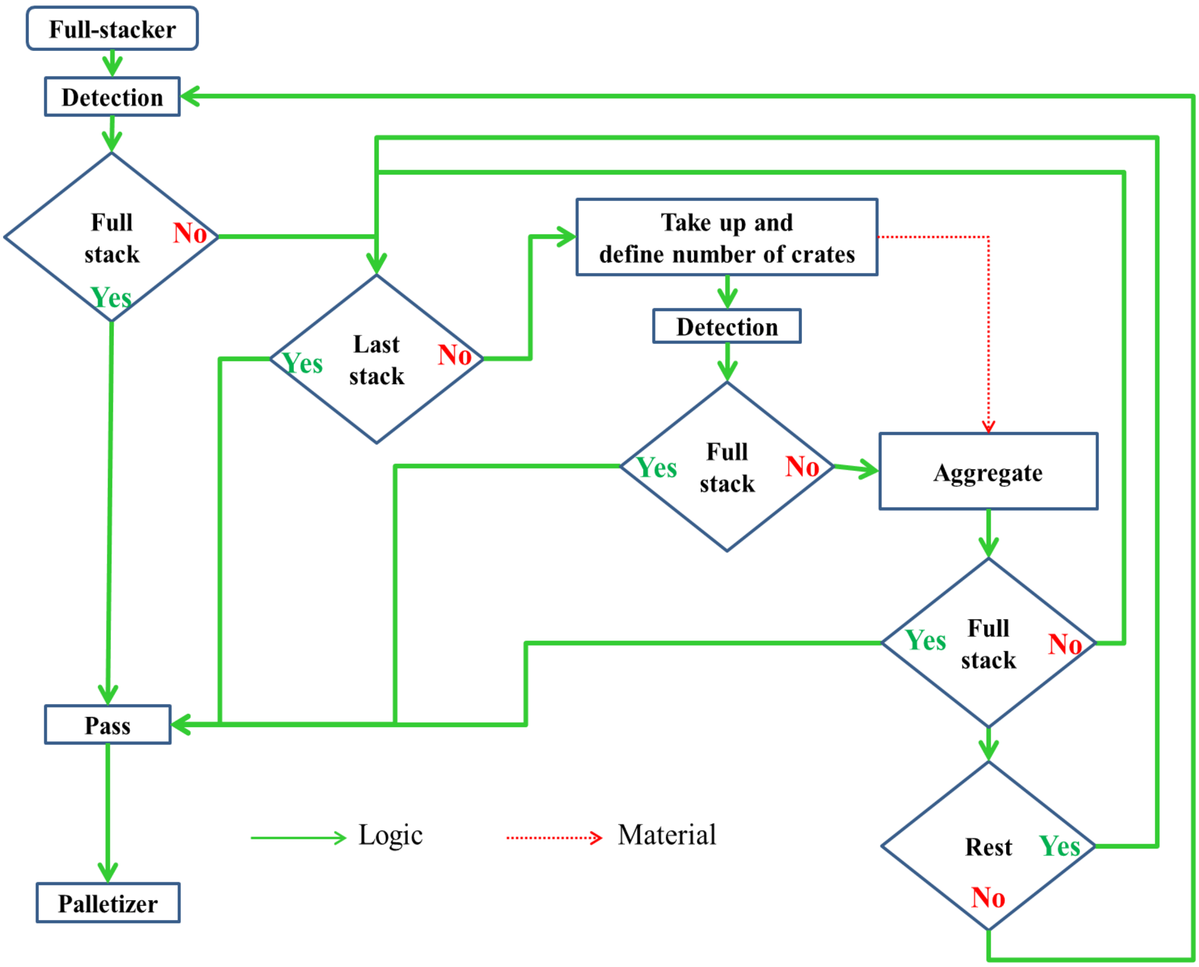


Figure 4.14 Flowchart of the working logic of a full-stacker

The technical parameters of full-stackers are determined based on the required time for all the processes that are executed by this machine. The general operating principle of the full-stacker is similar to the general operating principle of a crate stacking robot such as the gantry robot picking system (see Figure 4.15).

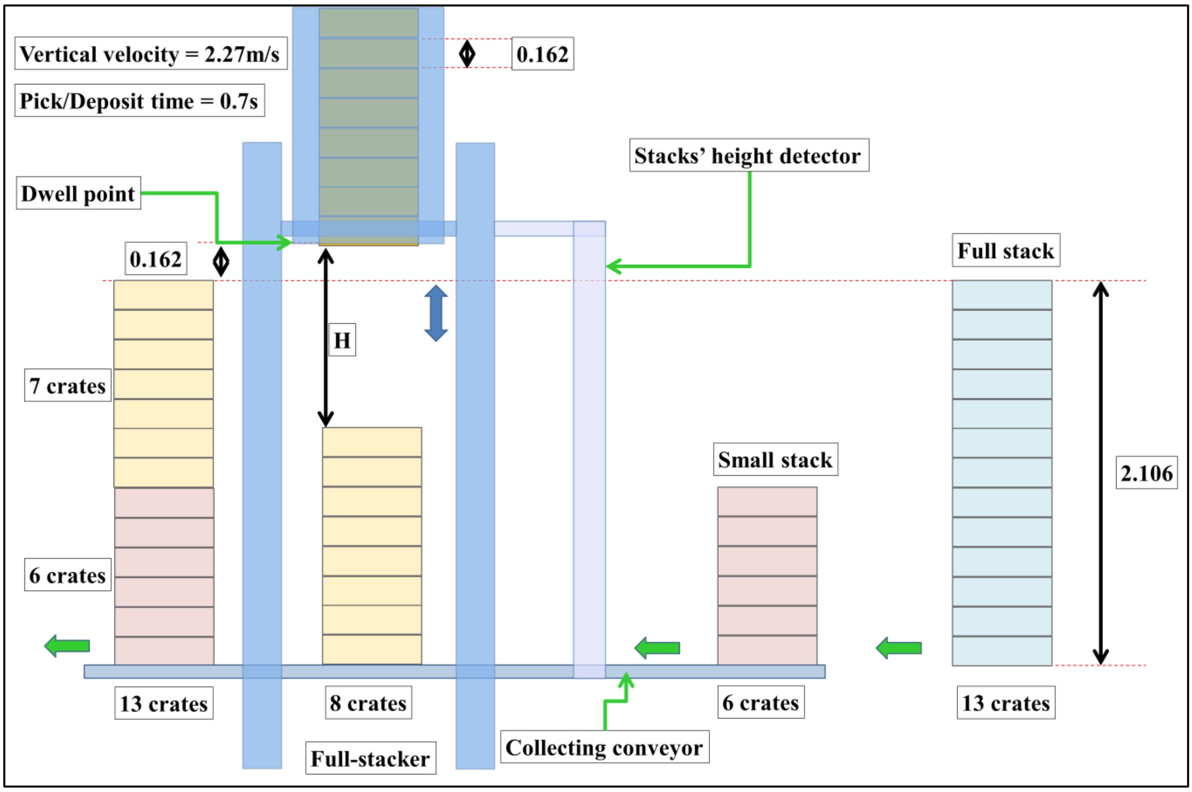


Figure 4.15 Layout of the full-stacker and the technical parameters

The time taken in re-stacking the small-stacks is divided into three stages: the ***first stage*** is the time picking the first small-stack and raising it to the highest point (the dwell point of the full-stacker), and this point at least is higher than the full-stack height. Regardless of the number of crates in the small stack, the required time for this stage is constant, because the full-stacker moves down to the lowest point to pick the small-stack and takes it up to the dwell point, where this stroke is constant. The number of crates in the first small-stack in the re-stacking process has no effect on the time required for this stage.

According to the technical parameters of a similar system (gantry robot picking system), the time is determined as follows: based on the layout of the full-stacker, which is explained in Figure 4.15, the full vertical displacement of a stroke is 2.27m and the vertical velocity is 2.27m/s. That means that the cycle time to pick and lift a small-stack by the full-stacker is 3 seconds. The lifting equals the traveling time of the picker back and forth (2 seconds), and this time is determined by dividing the vertical displacement of the picker stroke (2.27m) multiplied by 2 by the vertical velocity of the picker (2.27m/s). The picking time that the picker needs to pick the small-stack is determined as 1 second.

The ***second stage*** is the required time to aggregate two small-stacks together to form one full-stack. This time is a changeable time. It depends on the number of crates that must be added to the next small-stack to form one full-stack. The time required for this stage depends on the state of the small-stack that must be aggregated to form the full-stack. There are thus three possibilities related to the states of the re-stacked small-stacks as follows

- The first two small-stacks form a full-stack without the rest of the crates. The required time of this state is equal to the traveling time of the picker back and forth plus the release time (1 second). The traveling time is estimated by dividing the vertical moved distance (back and forth) by the vertical velocity of the picker. This vertical moved distance is determined based on the missed number of crates that must be added to the second small-stack to form a full-stack, where this number is the same as the number of the crates in the full-stacker at that time. Based on the full-stacker layout explained in Figure 4.15, the vertically moved distance is determined by multiplying the number of missed crates plus one by the height of a stacked crate.
- The first two small-stacks form a full-stack with the rest of the crates. The required time of this state is equal to the required time for the previous stage plus the time required for disassembling the rest of the crates from the newly formed full-stack. The rest of the disassembling time is only 1 second, which is required for the picker to pick the rest, where the traveling time of the rest of crates is already included in the time of the previous stage.
- The first two small-stacks do not have enough crates to form a full-stack. If the number of crates in the full-stacker is not enough to form one full-stack with the next small-stack, the full-stacker aggregates these two small-stacks together and takes them up in order to await a new small-stack that is aggregated to form one full-stack. The time required for this state is determined by calculating the traveling time of the picker back and forth plus the release time (1 second) and the pick time (1 second). The traveling time for this state is similar to the traveling time of the picker in the first stage, where the picker moves from the dwell point to the lowest point. The total time required for this state is 4 seconds, where the vertical traveling distance and velocity of the picker equals the same vertical traveling distance and vertical velocity (2.27m/s) in the first stage. When the picker of the full-stacker moves down to reach the aggregation point with the new small-stack, it aggregates the two stacks together. This process takes about 1 second, then the picker moves down to reach the base crate into the new small-stack (the lowest point in the stroke). The picker then picks all the crates and takes them up to the highest point in the stroke (the dwell point of the full-stacker), where the pick time and the release time are similar (1 second).

The ***third stage*** is the time required to release the last small-stack or the rest of crates within the full-stacker. This stage is similar to the first stage, and it takes the same time (3 seconds), where the picker of the full-stacker moves down from the dwell point to the lowest point, releases the rest of crates there and comes back to the dwell point. The required time for this stage is a constant. It doesn't depend on the number of crates within the full-stacker, because the number of recent crates within the full-stacker has no effect on the stroke distance of the picker or on the release time of the last stack, which may have only one crate.

4.5.9 Technical parameters of the palletizer

The palletizer is the last station of the OPP. All stacks passing through the full-stacker will reach the palletizing machine, which is installed at the end point of the collecting conveyor in the use-case model. The task of this machine is collecting every four stacks together on one pallet. Sometimes, fewer than four stacks need to be collected on one pallet. This situation occurs if the number of required stacks is less than four or if the number of the last required stacks is not enough to form a full pallet (less than four stacks). The minimum required throughput of this machine must be at least equal the maximum throughput of the use-case model, and therefore, the minimum required throughput of the palletizer must be at least 288pallets/h. The operational principle of the palletizer and the de-palletizer is similar, because they have the same mechanical design. A standard palletizing machine for stacks could be installed, but, the throughput of this machine must be not lower than the required. Two or more palletizing machines or other palletizing principles could be used to reach the required throughput.

4.6 ACCPS Use-Case Model Calculations

Based on the final layout and design of the ACCPS use-case model and the technical parameters of all parts of this use-case model, many performance indicators related to this use-case model are investigated in order to evaluate the ACCPS. The required areas, the storage density or the storage space utilization rate, the throughput of the use-case model and the costs of the use-case model have been calculated. The basic assumptions, the analytical techniques and the calculation methodologies that have been used in this section, have been explained in their related sections.

4.6.1 Required areas and space utilization rate

According to the described layout of the ACCPS in Figure 3.6 and the final described layout of the use-case model in Figure 4.3, the required area of the whole use-case model and the required area of the storage area of the use-case model are calculated as follows:

The area required for the whole use-case model

Based on the final described layout of the use-case model in Figure 4.3, the total length of the required area is 17.4m and the total width is 25.1m. These dimensions are taken without considering the dimensions of the feeding conveyor to the de-palletizer and the output conveyor from the palletizer, and therefore the minimum required area to apply the use-case model discussed in this research is 43,674m^2.

The space required for the storage area (cells area)

This area is calculated by multiplying its length by its width. The length of this area is equal to the length of one cell multiplied by the number of installed cells on one conveyor. The width of this area is determined by multiplying the width of one storage line (main conveyor with cells) by the number of installed storage lines (main conveyors), plus the total tolerances added to the width of every storage line multiplied by the number of the storage lines, plus the width of one maintenance hallway multiplied by the number of these maintenance hallways in the whole ACCPS use-case model (see Figure 4.16).

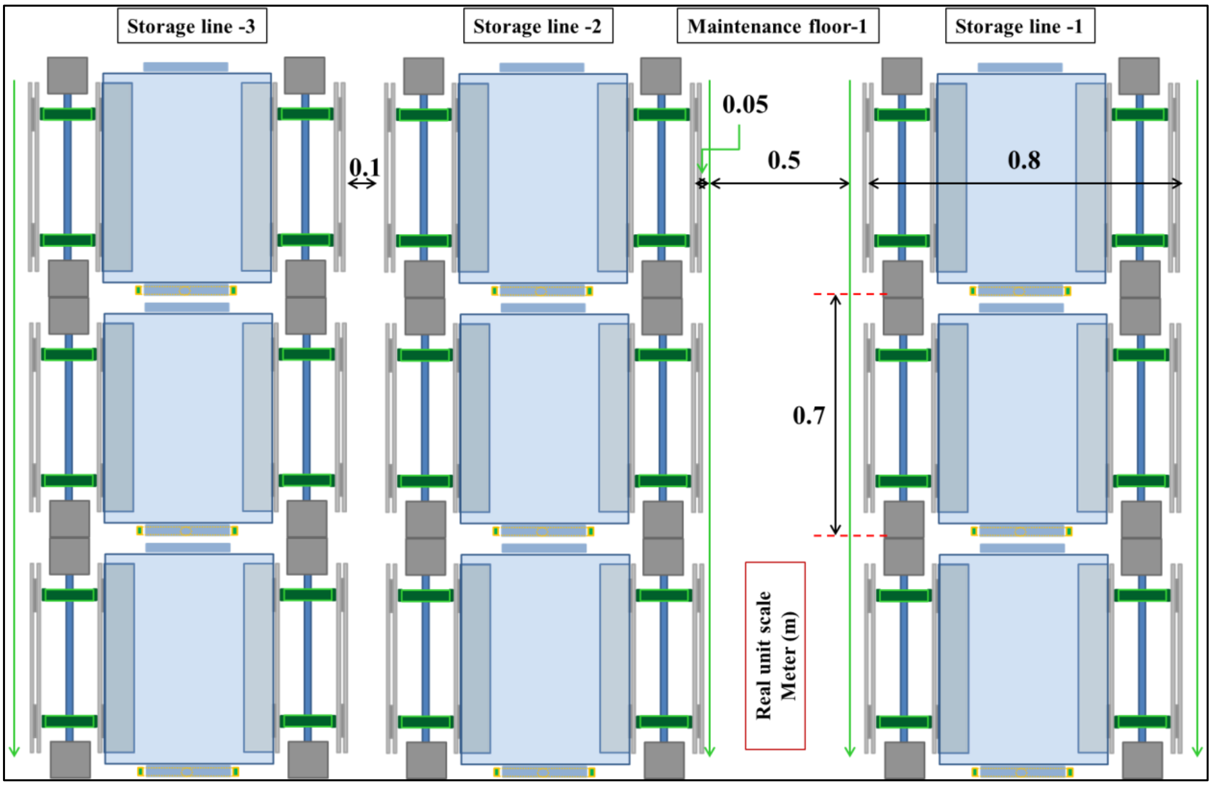


Figure 4.16 Top view of three storage lines from ACCPS use-case model

Therefore, and based on the technical parameters of the ACCPS use-case model that discussed in this research, the minimum required *storage area* is calculated as follows

$$SA^{min.req} = SA^{l} * SA^{w}, \tag{4.8}$$

$$SA^{l} = SC^{l} * \ Nr^{cells/line} , \tag{4.9}$$

and

$$SA^{w} = (SL^{w} * \ Nr^{SL}) + (MH^{w} * Nr^{MH}) + (Nr^{SL} * t) , \tag{4.10}$$

where $SA^{min.req}$ is the minimum required area of the storage part, SA^{l} is the length of the storage area, SA^{w} is the width of the storage area, SC^{l} is the length of the storage cell (0.7m), $Nr^{cells/line}$ is the number of storage cells per main conveyor or storage line (10cells/conveyor), SL^{w} is the width of the storage line (0.8m), Nr^{SL} is the number of storage lines (10 lines), MH^{w} is the width of the maintenance hallway (0.5m), Nr^{MH} is the number of maintenance hallways (5 hallways) and t is the total tolerance added to the width of every storage line in order to avoid conflict between the two storage lines, when they are installed back to back (0.1m).

Then,

$$SA^{l} = 7m ,$$

$$SA^{w} = 11.5 ,$$

and

$$SA^{min.req} = 80.5 \, m^{2} .$$

The capacity of the use-case model $(\boldsymbol{C^{model}})$

The capacity of the use-case model is determined by multiplying the number of cells in the use-case model ($Nr^{cells/model} = 100$ cells) by the capacity of the cell ($C^{cell} = 52$crates) as follows

$$C^{model} = Nr^{cells/model} * C^{cell} , \tag{4.11}$$

then

$$C^{model} = 5200 \, crates .$$

The storage density of the storage area $(\boldsymbol{d^{SA}})$

The storage density is determined via the percentage of the space volume used by the stored crates from the total space volume of the storage area. The volume of the storage area (V^{SA}) is calculated by multiplying the storage area by the height of the use-case model (H^{model}). The height of the use-case model is calculated by multiplying the height of storage position (0.25m) by the number of storage positions within one cell plus one (53 positions), plus the height of the main conveyor (0.5m). Then, *the storage density of the storage area* (d^{SA}) and *the volume of the storage area (V^{SA})* are calculated as follows

$$\mathrm{d}^{SA} = \frac{\mathrm{V}^{\mathrm{crates/model}}}{V^{SA}} , \tag{4.12}$$

and

$$V^{SA} = SA^{min.req} * H^{model} , \tag{4.13}$$

where

$$V^{SA} = 80.5 * 13.75 = 1106{,}87m^3 .$$

The used *space volume* of the stored crates is calculated as follows

$$\mathrm{V}^{\mathrm{crates/model}} = \mathrm{C}^{\mathrm{model}} * \mathrm{v}^{\mathrm{crate}} , \tag{4.14}$$

and then,

$$\mathrm{V}^{\mathrm{crates/model}} = 5200 * 0.042 = 218.4\mathrm{m}^3,$$

where $\mathrm{V}^{\mathrm{crates/model}}$ is the used space volume of the stored crates and $\mathrm{v}^{\mathrm{crate}}$ is the volume of a stored crate.

Then,

$$\mathrm{d}^{SA} = \frac{\mathrm{V}^{\mathrm{crates/model}}}{V^{SA}} = 0.197 .$$

If the storage lines are re-designed to be movable lines, the storage density of the ACCPS use-case model would increase to 25%, but, the costs of the system will also increase.

4.6.2 Expected cycle time and throughput of the ACCPS use-case model

A mathematical model has been designed to determine the expected cycle time of the OPP and the expected throughput of the ACCPS use-case model. The maximum throughput of the whole use-case model is easily calculated by determining the throughput of one cell per line multiplied by the number of the storage lines in the use-case model. In accordance with the speed of the cells and conveyors and the traveling displacements of the moved SKUs (from cells to output point and conversely from the input point to the cells), the required number of kinetic steps and the time intervals along the path of the moved SKUs are easily calculated. The path of the SKU movements during either the storage or retrieval process is divided into many steps. The time for every step is calculated according to the average velocity and displacement of this step. In order to determine the total time of a storage or retrieval process for a number of required crates, all kinetic steps of every moved crate are considered. The kinetic steps are then converted to time intervals in order to determine the total time for the whole process. A simple logic has been used to create the mathematical model and to explain the calculation methodology. In order to avoid complexity and create a simple mathematical model, the layouts of the input and output area of the use-case model are slightly changed. The de-stacking and stacking machines were deleted from the layout of the ACCPS use-case model, and the distributing conveyor and collecting conveyor are directly connected to the main conveyors with a velocity of 2.5m/s. In order to achieve the goals, the new layout of the use-case model is formed by using ten VICs to form one storage line, and ten lines to form the whole use-case model, where every two lines are combined to form one aisle with a free area (maintenance hallway) for maintenance work as shown in Figure 4.17.

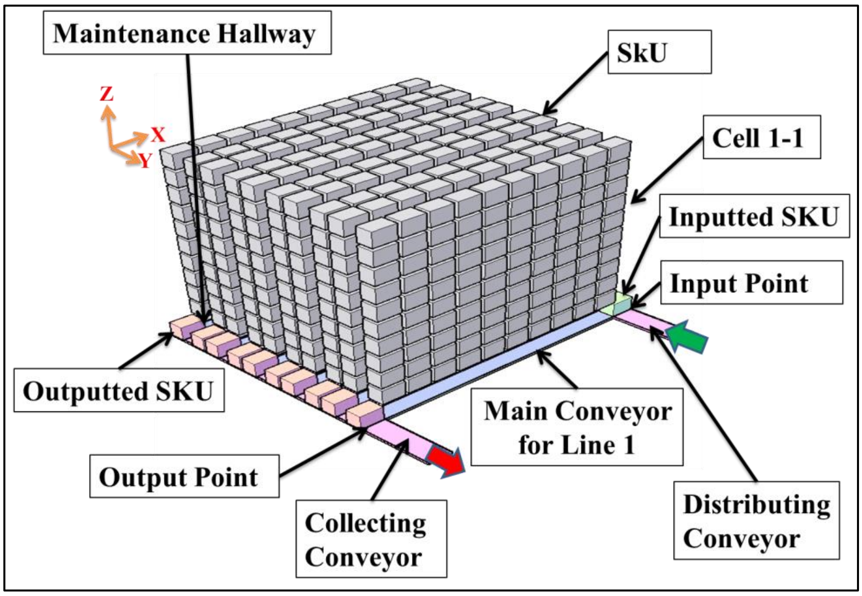


Figure 4.17 3D layout of the ACCPS use-case model

In this use-case model, the storage units (SKUs) are plastic crates (each crate has a length of 0.6m, a width of 0.4m and a height of 0.175m), and many crates are stored in one cell. The dimensions of a storage position within the cell are determined as 0.65m long, 0.45m wide and 0.25m high. The dimensions of the cell boundary are determined as 0.7m long, 0.8m wide. The height of the cell is determined based on the cell capacity. The maintenance hallway width is determined as 0.5m. 5 centimeters is used as a fixed tolerance on two sides of every storage line to avoid conflict between the elevation systems of the cells on different lines that are installed back to back. The vertical velocity of the cell (up and down) is determined to be 0.25m/s, the horizontal velocity of the main conveyor is determined to be 0.5m/s, and the distributing and collecting conveyor speed is determined to be 2.5m/s.

Methodology

Assuming that the all cells have the same capacity, the same load (the same number of the total required crates), and the same probability (to order the same number of crates), the retrieval and storage processes will have the same behavior and conditions. The mathematical model created will represent the two processes. The logic procedures that are applied to create the mathematical model are as follows

- Determining the centralized cell in the layout of the use-case model, this cell represents the center point of the use-case model according to the number of required crates (the symmetric point according to the load distribution)
- Counting the kinetic steps along the path of the crates from the first storage position in the centralized cell to the output point
- Making a table of these steps for a number of crates
- Finding the mathematical equation that represents these cases for every possible number of crates
- Converting the kinetic steps to time-steps by dividing the distance of these steps by their velocities in order to determine the time interval of every step
- Aggregating the time intervals and dividing by the number of the crates to determine the average OP time for one crate

According to the layout of the use-case model illustrated in Figures 4.18 and 4.19, the layout is designed based with a *U-shaped flow*, where there is no effect on the results or the procedures if the material flow is changed to an *I-shaped flow*. Based on the layout, centralized cells cannot be directly assigned, but there are two cells whose average represents the centralized cell for whole use-case model. These two cells are cell_5 on conveyor_5 (cell55) and cell_6 on conveyor_6 (cell66) as shown in the Figures 4.18 and 4.19.

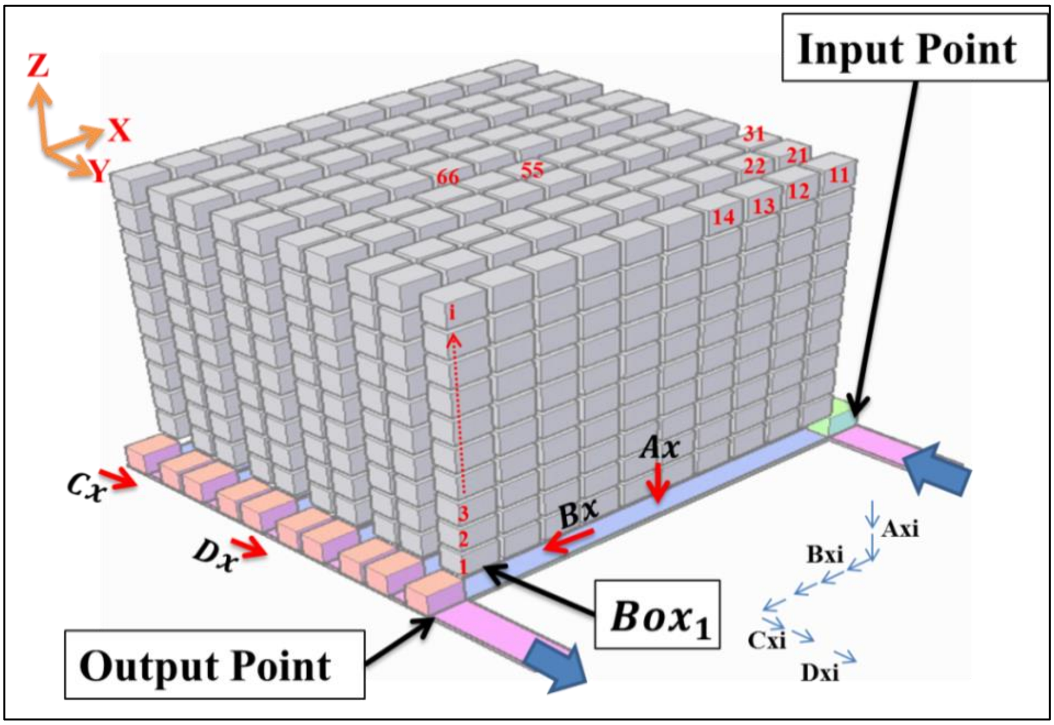


Figure 4.18 3D layout of the use-case model

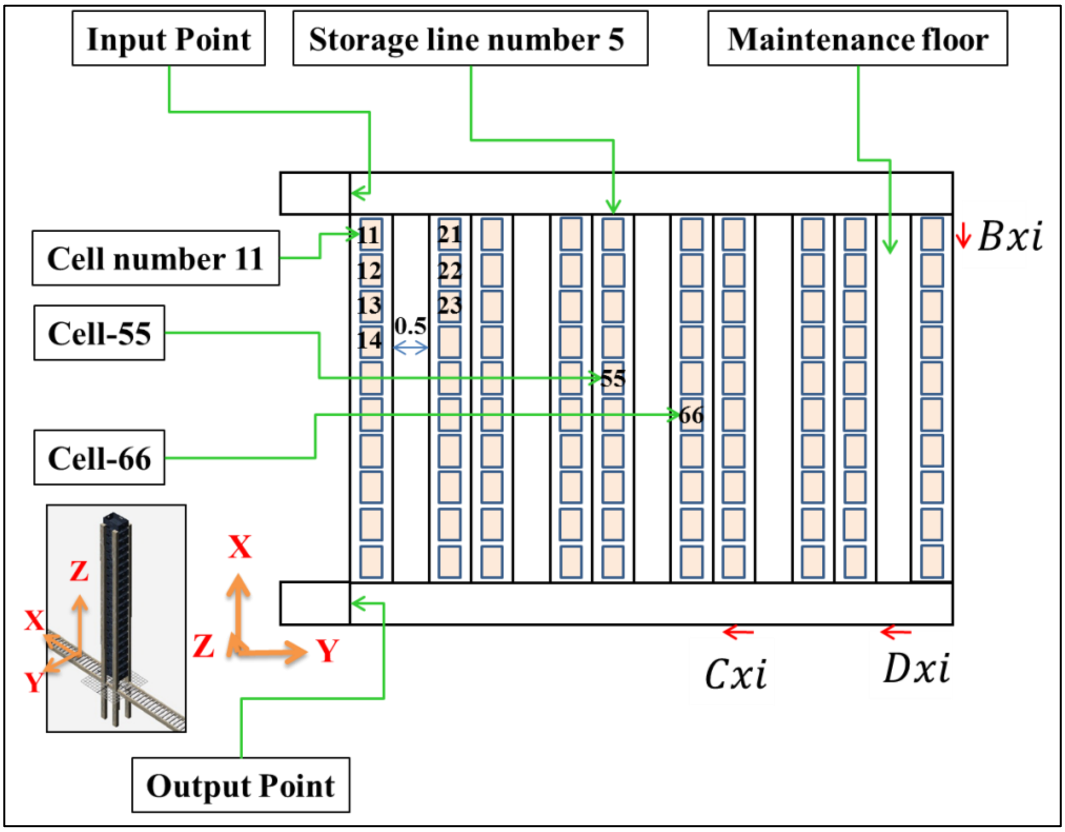


Figure 4.19 Top view of the use-case model

To execute the procedures in the methodology, the notations used, along with their descriptions, are presented as follows

- Box_i: i is the number of stored crates within the cell. According to their locations in the cell, the counting starts from the bottom, where $i = 1,2,3 \dots$.
- Ax: is the number of vertical kinetic steps that the box for number i (Box_i) needs to reach the main conveyor.
- Bx: is the number of horizontal kinetic steps on the main conveyor, which Box_i needs to reach the collecting conveyor.
- Cx: is the number of horizontal kinetic steps on the collecting conveyor, equivalent to the storage line width, which Box_i needs to reach the output point.
- Dx: is the number of horizontal kinetic steps on the collecting conveyor equivalent to the maintenance hallway width, which Box_i needs to reach the output point.
- Ex: is the number of waiting steps, which Box_i needs to wait within the cell, due to conflict with advanced crates.

In the next two steps of the methodology (number_2 and number_3) for cell66, the movement behavior for the first ten retrieved crates is summarized in Table 4.5.

Table 4.5 The movement behavior of the first ten retrieved crates from cell66

Events / Box Nr.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	
1	A1	B1	B2	B3	B4	B5	C1	D1	C2	C3	D2	C4	C5	D3	C6	END																			
2	A2	E1	A1	B1	B2	B3	B4	B5	C1	D1	C2	C3	D2	C4	C5	D3	C6	END																	
3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	C1	D1	C2	C3	D2	C4	C5	D3	C6	END															
4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	C1	D1	C2	C3	D2	C4	C5	D3	C6	END													
5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	C1	D1	C2	C3	D2	C4	C5	D3	C6	END											
6	A6	E5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	C1	D1	C2	C3	D2	C4	C5	D3	C6	END									
7	A7	E6	A6	E5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	C1	D1	C2	C3	D2	C4	C5	D3	C6	END							
8	A8	E7	A7	E6	A6	E5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	C1	D1	C2	C3	D2	C4	C5	D3	C6	END					
9	A9	E8	A8	E7	A7	E6	A6	E5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	C1	D1	C2	C3	D2	C4	C5	D3	C6	END			
10	A10	E9	A9	E8	A8	E7	A7	E6	A6	E5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	C1	D1	C2	C3	D2	C4	C5	D3	C6	END	

Table 4.5 illustrates the total events for the first ten crates retrieved from cell66. The first event for crate_1 is the move down to reach the main conveyor (event: A1), where A as a vertical kinetic step is equivalent to the height of the crate storage position within the cell. At the same time, all crates within the cell are moving down with it (events: A2, A3…). If crate_1 is transported one step horizontally on the main conveyor (event: B1), the other crates will be waiting in the cell without any movement (events: E1, E2…), where B as a horizontal kinetic step is equivalent to the cell length (0.7m) and E as a waiting time is equivalent to the time of the A event. When crate_1 reaches the collecting conveyor, it needs many kinetic

steps to reach the output point (events: C1, C2…, and C6; and events: D1, D2, and D3). Some of these steps are defined as C and others as D, where C is a kinetic step on the collecting conveyor equivalent to the width of a storage line plus the tolerance of the two sides of this line, and D is a kinetic step on the collecting conveyor equivalents to the width of the maintenance hallway.

The numbers of kinetic steps that the first ten retrieved crates executed along the retrieval path from cell66 to the output point are determined and explained in Table 4.6, based on Table 4.5.

Table 4.6 Number of kinetic steps for the first ten boxes from Cell66

$Box\ Nr$	Ax	Bx	Cx	Dx	Ex
1	1	5	6	3	0
2	2	5	6	3	1
3	3	5	6	3	2
4	4	5	6	3	3
5	5	5	6	3	4
6	6	5	6	3	5
7	7	5	6	3	6
8	8	5	6	3	7
9	9	5	6	3	8
10	10	5	6	3	9

Ax: number of vertical kinetic steps, Bx: number of horizontal kinetic steps on the main conveyor, Cx: number of horizontal kinetic steps on the collecting conveyor equivalent to the storage line width, Dx: number of horizontal kinetic steps on the collecting conveyor equivalent to the maintenance lane width and Ex: number of waiting steps.

In order to execute methodology procedure number_4, the movement behaviors of the retrieved crates from cell66 for crate_1, crate_2, and crate_10 are determined via the following mathematical formulas

$$Nr.K.S_{Box_1}^{cell66} = 1 * Ax + 5 * Bx + 6 * Cx + 3 * Dx + 0 * Ex\ ,$$

$$Nr.K.S_{Box_2}^{cell66} = 2 * Ax + 5 * Bx + 6 * Cx + 3 * Dx + 1 * Ex\ ,$$

and

$$Nr.K.S_{Box_{10}}^{cell66} = 10 * Ax + 5 * Bx + 6 * Cx + 3 * Dx + 9 * Ex\ .$$

where $Nr.K.S_{Box_1}^{cell66}$ is the total number of kinetic steps for crate_1 along the retrieving path from cell66 to the output point (likewise for crate_2 and crate_10).

Similarly, the total number of kinetic steps for $\mathrm{Box_i}$ is determined as follows

$$Nr.K.S\,_{Box_i}^{cell66} = i * Ax + 5 * Bx + 6 * Cx + 3 * Dx + (i-1) * Ex\,, \tag{4.15}$$

where $Nr.K.S\,_{Box_i}^{cell66}$ is the total number of kinetic steps for an order along the retrieving path from cell66 to the output point, where the number of required crates is equal to i, and $i = 1,2,\ldots\infty$.

Then, the average number of kinetic steps for one crate is determined as follows

$$Ave.Nr.K.S\,_{one\,box}^{cell66} = \frac{i * Ax + 5 * Bx + 6 * Cx + 3 * Dx + (i-1) * Ex}{i}\,, \tag{4.16}$$

In order to satisfy procedure number_5 in the methodology, the kinetic steps are converted to time-steps. A kinetic step is converted to a time-step by dividing the displacement of the kinetic step by the applied velocity of the step location along the retrieval path. According to the definition of every kinetic step, the times of all kinetic steps are determined as follows

$$Ax = \frac{h}{v_v} = \frac{0.25}{0.25} = 1\,s\,,$$

$$Bx = \frac{l}{v_h} = \frac{0.7}{0.5} = 1.4\,s\,,$$

$$Cx = \frac{SL^w + t}{v^{col.con}} = \frac{0.8 + 0.1}{2.5} = 0.36\,s\,,$$

$$Dx = \frac{MH^w}{v^{col.con}} = \frac{0.5}{2.5} = 0.2\,s\,,$$

and

$$Ex = Bx = \frac{L}{v_h} = \frac{0.7}{0.5} = 1.4\,s\,,$$

where

- h: vertical crate displacement within the cell (0.25m)
- v_v: vertical crate velocity (0.25m/s)
- l: horizontal crate displacement within the cell (0.7m)
- v_h: horizontal crate velocity (0.5m/s)
- SL^w: width of the storage line (0.8m)
- t: *the* total tolerance added to the width of every storage line (0.1m)
- $v^{col.con}$: velocity of the collecting conveyor (2.5m/s)
- MH^w: width of the maintenance hallway (0.5m)

In order to determine the minimum picking time and the average picking time of an order from cell66, the last rule in the methodology logic is applied. Instead of the time values of the kinetic steps in the two previous equations, the expected OP time for an order, when the number of required crates equals i, and the average picking time of one crate from this order is determined as follows

$$Min.P.T\,{}^{cell66}_{Box_i} = (i * 1) + (5 * 1.4) + (6 * 0.36) + (3 * 0.2) + \big((i-1) * 1.4\big), \qquad (4.17)$$

then

$$Min.P.T\,{}^{cell66}_{Box_i} = (2.4i)\ s + 8.36\ s\,,$$

and

$$Ave.P.T\,{}^{cell66}_{one\ box} = 2.4 + \frac{8.36}{i}\,, \qquad (4.18)$$

where $Min.P.T\,{}^{cell66}_{Box_i}$ is the minimum picking time of an order from cell66, and the number of required crates in this order is equal to i and $Ave.P.T\,{}^{cell66}_{one\ box}$ is the average picking time of one box (crate).

For example, the total picking time and the average picking time of an order from cell66, where the number of required crates is 3, are calculated as follows

$$Min.P.T\,{}^{cell66}_{Box_i} = (2.4 * 3)\ s + 8.36\ s = 15.56\ s\,,$$

and

$$Ave.P.T\,{}^{cell66}_{one\ box} = 2.4 + \frac{8.36}{3} = 5.19\ s/crate\,.$$

By executing the same logic rules for cell55, the movement behaviors of the first ten crates retrieved along the retrieval path from cell_5 on conveyor_5 to the output point are summarized in Table 4.7.

Table 4.7 The movement behavior of the first ten retrieved crates from cell55

Event / Box Nr.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	A1	B1	B2	B3	B4	B5	B6	C1	C2	D1	C3	C4	D2	C5	END																		
2	A2	E1	A1	B1	B2	B3	B4	B5	B6	C1	C2	D1	C3	C4	D2	C5	END																
3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	B6	C1	C2	D1	C3	C4	D2	C5	END														
4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	B6	C1	C2	D1	C3	C4	D2	C5	END												
5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	B6	C1	C2	D1	C3	C4	D2	C5	END										
6	A6	E5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	B6	C1	C2	D1	C3	C4	D2	C5	END								
7	A7	E6	A6	E5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	B6	C1	C2	D1	C3	C4	D2	C5	END						
8	A8	E7	A7	E6	A6	E5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	B6	C1	C2	D1	C3	C4	D2	C5	END				
9	A9	E8	A8	E7	A7	E6	A6	E5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	B6	C1	C2	D1	C3	C4	D2	C5	END		
10	A10	E9	A9	E8	A8	E7	A7	E6	A6	E5	A5	E4	A4	E3	A3	E2	A2	E1	A1	B1	B2	B3	B4	B5	B6	C1	C2	D1	C3	C4	D2	C5	END

The total numbers of kinetic steps for the first ten retrieved crates along the retrieving path from cell55 to the output point are summarized in Table 4.8. This table represents the results of Table 4.7.

Table 4.8 Number of kinetic steps for the first ten boxes from Cell55

$Box\ Nr$	Ax	Bx	Cx	Dx	Ex
1	1	6	5	2	0
2	2	6	5	2	1
3	3	6	5	2	2
4	4	6	5	2	3
5	5	6	5	2	4
6	6	6	5	2	5
7	7	6	5	2	6
8	8	6	5	2	7
9	9	6	5	2	8
10	10	6	5	2	9

Ax: number of vertical kinetic steps, Bx: number of horizontal kinetic steps on the main conveyor, Cx: number of horizontal kinetic steps on the collecting conveyor equivalent to the storage line width, Dx: number of horizontal kinetic steps on the collecting conveyor equivalent to the maintenance lane width and Ex: number of waiting steps.

According to the results of the movement behaviors for the retrieved crates, the mathematical equation that represents any number of retrieved crates is determined as follows

$$Nr.K.S\,_{Box_i}^{cell55} = i * Ax + 6 * Bx + 5 * Cx + 2 * Dx + (i-1) * Ex\,, \tag{4.19}$$

and the average number of kinetic steps for one crate is determined as follows

$$Ave.Nr.K.S\,_{one\ box}^{cell55} = \frac{i * Ax + 6 * Bx + 5 * Cx + 2 * Dx + (i-1) * Ex}{i}.$$

The kinetic steps from all cells with the same type of movement have the same time value, because they have the same displacement and velocity value. By converting these kinetic steps to time-steps - by dividing a step's displacement by its velocity - the expected OP time of an order, where the number of required crates is equal to i, and the average picking time of one crate is determined as follows

$$Min.P.T\,_{Box_i}^{cell55} = (i * 1) + (6 * 1.4) + (5 * 0.36) + (2 * 0.2) + \big((i-1) * 1.4\big),$$

then

$$Min.P.T\,_{Box_i}^{cell55} = (2.4i)\ s + 9.2\ s\,,$$

and

$$Ave.P.T\,_{one\ box}^{cell55} = 2.4 + \frac{9.2}{i}.$$

For example, the total picking time and the average picking time of an order from cell55, where the number of the required crates is 3, are calculated as follows

$$Min.P.T\,{}^{cell55}_{Box_i} = (2.4 * 3)\ s + 9.2\ s = 16.4\ s\ ,$$

and

$$Ave.P.T\,{}^{cell55}_{one\ box} = 2.4 + \frac{9.2}{3} = 5.47\ s/crate\ .$$

It is noted here, that there is a constant time (2.4) multiplied by the number of the retrieved crates and another variable value of time related to the cell location. The first term represents the time that the stored crate needs to leave the cell's boundary. The other term represents the time that the retrieved crate needs to leave the use-case model, and is related to the cell's location within use-case model. The value of this term will therefore be maximum for the farthest cell from the outlet, and minimum for the cell nearest to the outlet. In order to represent the whole use-case model, the average value for all cells must be determined. If the load is uniformly distributed in the cells of the use-case model, the value of the second term for the whole use-case model is determined by determining the average value of this term for the cell66 and cell55. The expected minimum OP time of an order and the average picking time of one crate from this order for the whole use-case model are thus determined as follows

$$Min.P.T\,{}^{Model}_{Box_i} = (2.4i)\ s + \frac{8.36 + 9.2}{2}\ s\ ,$$

then

$$Min.P.T\,{}^{Model}_{Box_i} = (2.4i)\ s + 8.78\ s\ , \tag{4.20}$$

and

$$Ave.P.T\,{}^{Model}_{one\ box} = 2.4\ s + \frac{8.78}{i}\ s\ , \tag{4.21}$$

where i is the total number of required crates.

For example, the total picking time and the average picking time of an order from the use-case model, where the total required crates is 3, are calculated as follows

$$Min.P.T\,{}^{Model}_{Box_i} = (2.4 * 3)\ s + 8.78\ s = 15.98\ s\ ,$$

and

$$Ave.P.T\,{}^{Model}_{one\ box} = 2.4 + \frac{8.78}{3} = 5.33\ s/crate\ .$$

If the number of required crates in an order from a cell on a storage line reaches infinity, the value of the average picking time for one crate reaches the minimum value. The minimum average picking time of a crate from use-case model is then determined as follows

$$Min.Ave.P.T\,_{one\ box}^{Model} = \lim_{i\to\infty}\left(2.4 + \frac{8.78}{i}\right), \tag{4.22}$$

then

$$Min.Ave.P.T\,_{one\ box}^{Model} = 2.4s\ .$$

Only at this time does the value of the throughput reach the maximum value, and therefore, the maximum throughput of the use-case model is determined via the maximum throughput of one storage line multiplied with the number of storage lines in the use-case model as follows

$$Thr_{model}^{max} = \frac{1h * 60 * 60}{2.4} * Nr^{SL}\ ,$$

then

$$Thr_{model}^{max} = \frac{1h * 60 * 60}{2.4} * 10\ ,$$

and

$$Thr_{model}^{max} = 15000\ crates/h\ .$$

In the optimal case of a single process per line, one crate is stored in or retrieved from a cell every 2.4 seconds. For a continuous storage or retrieval process, the maximum throughput of a storage line in the use-case model is therefore 1500 crates per hour, and the maximum throughput of the entire use-case model is 15000 crates per hour. In the optimal case of the double process per line, where the storage process is parallel to the retrieval process for two different cells on the same storage line, however, the maximum throughput of the storage line per hour is 3000 crates, and the maximum throughput of the entire use-case model is 30000 crates per hour.

Reaching the maximum throughput in reality requires solving several problems and conflicts such as: the idle problem of some storage lines, limited capacities of the cells, low required number of crates per order-line, and low probability of continuous occurrence of the double process for all lines over the picking process duration. Nevertheless, the effects of these problems could be minimized by optimizing the solutions of the storage location assignment problem and order picking strategies. As a result of the mathematical model, the average picking time has an inversely proportional relationship with the number of the required crates.

4.6.3 Initial cost of the ACCPS use-case model

The cost calculation methodology used to calculate the initial cost of the ACCPS use-case model, is based on the real price of the system elements. The costs of the standard parts were directly determined based on the supplier's price catalogs, and the costs of the other parts were determined according to real offers from the suppliers. The storage cell is the most important element in the system. It consists of a structure, a drive system (motor and gearbox), an actuator (stopper), an elevator system (double pair of chains or belts), sensor units and PLC. The costs of the cell drive systems, which consist of helical-bevel gear motors, assembled cables, converters/options/accessories, compact controllers, interface converters, USB and control panels, are identified according to the *SEW-EURODRIVE* company offer, which is summarized in Table 4.9 as follows

Table 4.9 Total cost of drive systems for the whole use-case model

Product	Code number	Cost per piece (Euro)	Quantity	Total cost (Euro)
Helical-bevel gear motor	K67CMP80S/BP/KY/AK0H/SB1	2,452.02- €	10 pieces	24,520.20 €
Assembled cable	Cable 13324535/20.0	173.25- €	10 pieces	1,732.50 €
Converter options accessories	MDX61B0055-5A3-4-00/DEH11B	2,040.15- €	10 pieces	20,401.50 €
Compact controllers	DHF41B/OMC41B-T0/UOH21B	1,400.00- €	1 piece	1,400 €
Interface converter USB	USB11A	95.00- €	1 piece	95 €
Control panel	DBG60B-01	119.00- €	1 piece	119 €
Total cost of a series of ten cells				48,268.20 €
Total cost of the ACCPS use-case model				**482,682 €**

According to Bastian (2006), the total costs of the structure frame of the cell and belt system with cantilevers for the 100 required storage cells are determined as shown in Table 4.10.

Table 4.10 Total cost of the structure frames and elevation belts with the cantilevers

Product	Code number	Cost per piece (Euro)	Quantity	Total cost (Euro)
Cell frame with belt and cantilevers	--	10,000	100 piece	1,000,000 €
Total cost of the ACCPS use-case model				**1,000,000 €**

According to the *Leuze Electronic GmbH* offer, the total cost of the required sensors and the support parts for the whole use-case model are as shown in Table 4.11.

Table 4.11 Total cost of the sensors and supports for the whole use-case model

Product	Code number	Cost per piece (Euro)	Quantity	Total cost (Euro)
Light barriers	50104698 PRK3B/6.7S8	87.00- €	100 piece	8,700 €
Reflectors	50022814 TKS 50X50	5.00- €	100 piece	500 €
Cables	50104524 K-DM8A-4P2m-PVC	8.00- €	100 piece	800 €
Total cost of the ACCPS use-case model				**10,000 €**

According to the *LINAK GmbH* offer, where a linear electric actuator is used as a crate stopper, the total cost of stoppers for the whole use-case model are as shown in Table 4.12.

Table 4.12 Total cost of the stoppers and supports for the whole use-case model

Product	Code number	Cost per piece (Euro)	Quantity	Total cost (Euro)
Linear Electric Actuators (LA23 with IC) + Cable + Cable securing	2362001065250B6	192.00 - €	100 piece	19,200 €
Total cost for the ACCPS use-case model				**19,200 €**

According to the *BECK Automation GmbH* offer, the controlling system for the whole use-case model consists of:

- Planning and design of electrical switchgear for controlling motors
- Valves and sensors for stock-picking with according to specifications
- Security features such as emergency stop, safety light curtains, safety doors
- Creating a complete wiring diagram in computer aided engineering system and environment planning software (EPLAN)
- Delivery of Rittal cabinets including all necessary equipment
- Delivery of all items such as feed, busbar systems and transformers
- Network devices, hardware, and wiring material and safety evaluation terminals,
- Delivery of two Siemens S7 400 PLC racks with all necessary fittings such as I /O cards, network cards for Profibus and ethernet

- Delivery of two Siemens touch multi-panels for operating the system
- Manufacturing, assembly and wiring of the cabinets in the workshop
- Create a European Conformity (CE) Declaration of Conformity

Based on this offer, the total cost of the control system for the whole use-case model is identified as shown in Table 4.13.

Table 4.13 Total cost of the controlling system for the whole use-case model

Product	**Total cost (Euro)**
For entire package (installation + cables + PLC + Rittal box+ assembly)	192,000 €
Total cost of the ACCPS use-case model	**192,000 €**

The costs of the required stacker, de-stacker, palletizer, and de-palletizer are determined based on standard machine costs. According to the price of the available machines at *Langhammer GmbH*, the total cost of the required machines is identified as shown in Table 4.14. The costs of equipment of the input area and output area are really very high, and therefore, equipment in these two areas depends on the needs of the application area. Where there are application areas, they don't require equipment in the input area, because of the manual palletizing process or they don't require equipment in the output area, because of the directly feeding of crates and not pallets. As for the output area, there is no need to install any machinery for some application areas, especially if the palletizing process is manually executed or the products are delivered to the customer in the form of crates and not pallets.

Table 4.14 Total cost of the stacker/de-stacker and palletizer/ de-palletizer for the whole use-case model

Product	**Code number**	**Cost per piece (Euro)**	**Quantity**	**Total cost (Euro)**
Crat de-stacker	KST 1	30,000- €	10 piece	300,000 €
Crate stacker	KE 1	30,000- €	10 piece	300,000 €
Crate full-stacker	----	100,000- €	1 piece	100,000 €
Pallet de-palletizer	DPA1	70,000- €	1 piece	70,000 €
Pallet palletizer	PA11	70,000- €	1 piece	70,000 €
Total cost for the use-case model				**840,000 €**

The conveyance system for the use-case model consists of many roller conveying modules. The distributing conveyor consists of many conveying modules, deflector diverters, and bends conveying modules. The total cost of this conveyor is identified based on the cost of all parts required to build it. The collecting conveyor has the same structure as the distribution conveyor, and the same cost, of course. The main conveyor consists of three conveying modules that have a simple structure for conveying crates. According to Bastian (2006), the total cost of all required standard conveying modules that are compatible with the ACCPS use-case model are as shown in Table 4.15.

Table 4.15 Total cost of the conveying system for the whole use-case model

Conveyor type	Total cost (Euro)
Distributing conveyor	24,000 €
Aisle conveyor (main conveyor)	13,000 €
Collecting conveyor	24,000 €
Conveyors before and after de-/stacker	15,000 €
Total cost for the ACCPS use-case model	**76,000 €**

After building the use-case model, a material flow management and control system is needed. A WMCS with full options for description, controlling, and analyzing every flow of goods and information, especially along the intra-logistics chain, is required. All the hardware and software components of the WMS must be integrated with the material flow controlling system and the control system of the use-case model.

The WMS costs are identified according to the *IFD-Group (IFD GmbH)* offer. The total considered costs for the WMS are identified and summarized as illustrated in Table 4.16, where the offered package of the material flow control and warehouse management function consists of software and licenses, hardware and system licenses, interface analysis and talks, database and interface design, travel costs, functional design, design/development system setup, customizing/implementation, created design documents, application development, and training.

Table 4.16 Total cost of the material flow control and warehouse management function

Product	Total cost (Euro)
IFD-WMS	175,700 €
Hardware (server)	27,000 €
Total cost for the ACCPS use-case model	**202,700 €**

The total initial cost of the ACCPS use-case model is a crucial factor in determining the benefits of this system and its potential for application. Initial cost is a crucial factor in comparison with the other competitive systems. ROI is a significant indicator, directly related to user preferences between the offered solutions, where the total initial cost is the basic factor in determining the ROI. The total initial cost of the ACCPS use-case model is summarized in Table 4.17.

Table 4.17 Expected total initial costs of the ACCPS use-case model

Product	**Total cost (Euro)**
Cells drive system	482,682 €
Cell frames with belt and cantilevers	1,000,000 €
Sensors and support parts	10,000 €
Stoppers and supports parts	19,200 €
Use-case model control system	192,000 €
Stacker/de-stacker and palletizer/de-palletizer	840,000 €
Use-case model conveying system	76,000 €
WMS	202,700 €
ACCPS use-case model total costs	**2,822,528 €**

Cost can vary depending on the features of the installed parts of the system, and the amount of installation work required. There are also additional costs to bear in mind, such as support costs and training fees. Nevertheless, the total initial cost compared to the throughput of the ACCPS use-case model indicates the super features of the ACCPS. In the end, warehouse managers will have to evaluate their costs in order to choose a solution that has the potential to demonstrate the highest cost effectiveness in driving efficiency, reducing manpower, and eliminating picking errors. After determination of the required criteria for all mechanical parts of the ACCPS use-case model and for controlling system and management system, the total costs of the whole use-case model are identified. The costs, the throughput, and the required area are the most important comparison criteria between the ACCPS and the other alternative solutions.

4.7 ACCPS Layout Design Algorithm

In order to determine the optimal ACCPS layout, a design algorithm is illustrated in Figure 4.20. This design algorithm is based on the SKU profile, pallet profile, minimum number of articles that must be processed in one picking period, maximum required throughput (for example per hour), horizontal and vertical velocity of the storage cell, and replenishment time. This algorithm determines the minimum required number of the cells and storage lines for optimizing the layout of the ACCPS use-case model.

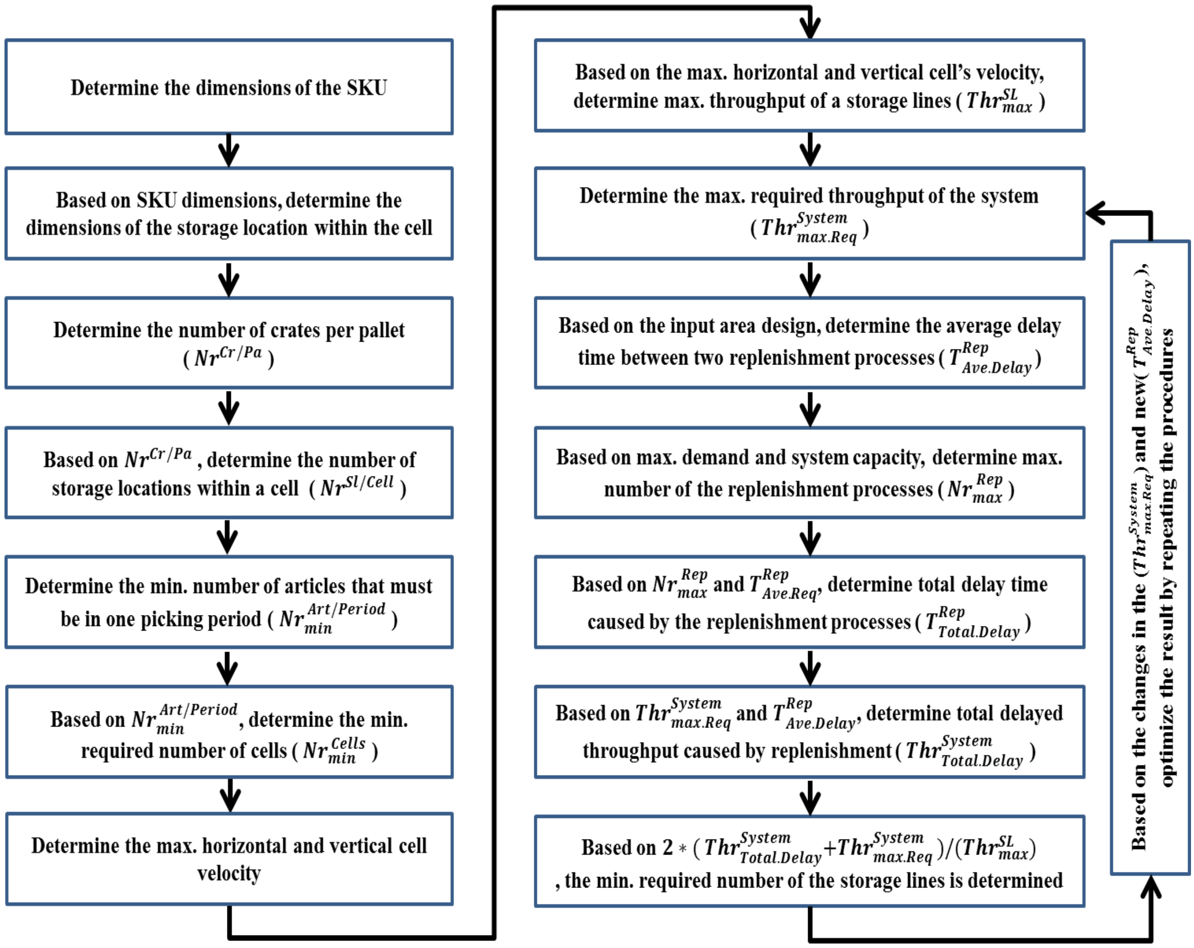


Figure 4.20 ACCPS layout design algorithm

In order to determine the minimum required number of storage lines using this algorithm, some assumptions should be identified:

- The preparation time for the replenished pallets before processing in the de-palletizing machine will be not considered.
- The output area of the system has no negative effect on the total throughput.
- The picking process is a continuous process for all customers without any breaks.

The algorithm procedures are thus defined as follows

- The dimensions of the storage locations within the cells are determined according to the dimensions of the handled crates, where the dimensions of the storage locations equal the dimensions of the SKUs plus the value of the tolerance.
- According to the number of standard crates in one pallet ($Nr^{cr/pa}$), the minimum number of required storage locations within the cell ($Nr_{min.req}^{sl/cell}$) is determined, where the capacity of the cell equals the number of crates in one pallet.

- The minimum number of the required cells ($Nr_{min.req}^{Cells}$) is determined according to the minimum number of articles that must be processed in one picking period ($Nr_{min}^{art/pp}$). The minimum number of articles in a picking period is determined based on the order profiles.
- The maximum throughput of a storage line (Thr_{max}^{SL}) is determined according to the horizontal and vertical velocity of the cell.
- The maximum required throughput of the ACCPS use-case model ($Thr_{max.Req}^{system}$) per hour is determined according to maximum demand (for example the maximum number of required crates per hour).
- The expected average delay time (in seconds) between two replenishment processes ($T_{Ave.Delay}^{Rep}$) is determined according to the input area design. This time represents the de-palletizing time needed for a replenished pallet in the de-palletizing machine and any other delay time related to the replenishment process, such as the time for preparing the pallets before the de-palletizing machine.
- According to total demand (crates), the capacity of the system (crates), and ($Nr^{Cr/Pa}$), determines the maximum number of replenishment processes per hour *(Nr_{max}^{Rep})* (replenished pallets per hour). The *(Nr_{max}^{Rep})* is determined by neglecting the capacity of the system from the total demand divided by the ($Nr^{Cr/Pa}$), then divided by total picking time.
- The total delay time caused by the replenishment processes is determine ($T_{Total.Delay}^{Rep}$) according to the ($\mathrm{Nr}_{\mathrm{max}}^{\mathrm{Rep}}$) and ($\mathrm{T}_{\mathrm{Ave.Delay}}^{\mathrm{Rep}}$). The total delay time caused by the replenishment processes is determined by multiplying (Nr_{max}^{Rep}) with ($T_{Ave.Delay}^{Rep}$), and then dividing the result by one hour (3600 seconds), thus the total delay time (hours) for the whole system is determined.
- The total delayed throughput caused by replenishment processes ($Thr_{Total.Delay}^{System}$) is determined according to the ($Thr_{max.Req}^{System}$) and ($T_{Total.Delay}^{Rep}$). The ($Thr_{Total.Delay}^{System}$) is calculated by multiplying the ($Thr_{max.Req}^{System}$) with the ($T_{Total.Delay}^{Rep}$) for the whole system**.**
- The expected minimum required number of the storage lines that must be installed is determine according to the ($Thr_{Total.Delay}^{System}$) and ($Thr_{max.Req}^{System}$). The expected minimum

required number of storage lines is determined as follows $\frac{2*(Thr_{Ave.Delay}^{System}+Thr_{max.Req}^{System})}{Thr_{max}^{SL}}$. The reduplication process is necessary, because there are two processes for every independent crate during the picking process (storage and retrieval).

- In order to refine and optimize the result based on new changes in the ($Thr_{max.Req}^{System}$) and ($T_{Ave.Delay}^{Rep}$), the procedures could be repeated from the point of determining the value of the ($Thr_{max.Req}^{System}$). The expected minimum required number of storage lines could be always optimized in order to compensate for new deviation in the maximum required throughput of the ACCPS and delayed throughput caused by replenishment.

Actually, because the fractions in the result of the (Nr_{min}^{SL}) will be always rounded away from zero, one optimization cycle could be sufficient to determine the optimal required number of the storage lines. More optimization cycles could change the result, however, especially if the fraction of the result is close closer to one and further away from zero.

For example: in order to optimize the design layout of the ACCPS use-case model for the first case study, where the total required crates is approximately 44640 crates in 8.5 hours, the design algorithm is used as follows

- SKU dimensions (600X400X175mm)
- Storage location dimensions equal SKU dimensions plus a tolerance 50-100mm. Then, the storage location dimensions are (700X450X250mm).
- Number of crates per pallet equals 52 crates. Then, the number of storage locations within a cell equals 52.
- According to the first case study, the minimum number of articles in one picking period is determined as 100 articles. The minimum number of required cells is thus100.
- Horizontal and vertical velocities are determined as 0.5 and 0.25m/s, respectively.
- Maximum throughput of a storage line is 1500 crates/h.
- Maximum required throughput is 5251.76 crates/h (44640/8.5)
- The expected average time delay between two replenishment processes is 12.5 seconds per process (equals the de-palletizing time for a pallet).
- The maximum number of replenishment processes is 89.23 processes/h.
- Total delay time caused by replenishment processes is determined as 0.31 operating hours.

- Total delayed throughput caused by replenishment processes is 1628.04 crates/h.
- The new maximum required throughput is equal to 6879.76 crates/h.
- The minimum expected number of required storage lines is 9.17, and therefore, the optimal layout of the ACCPS is determined as 100 cells installed on 10 lines.

5 SIMULATION MODEL AND CASE STUDIES

In this chapter a simulation model is designed in order to evaluate the ACCPS. The evaluation is based on the data from two real case studies. Many simulation scenarios are tested and discussed in order to optimize the model. Finally, the results of the simulation model are discussed and evaluated.

5.1 Introduction

Thanks to the evolution of IT and computerized systems, many DC designs, and the arrangement and management of automated material handling systems (AMHSs) are highly developed, for many practical reasons. In DC, both customer requirements and system designs play an important role in controlling different types of products for different customers. It is important to design systems that take the workload into consideration.

A large number of complicated rules, as well as a new development procedure to control the DC, are required in order to achieve high throughput using AMHSs. A comprehensive algorithm is thus necessary to generate the appropriate control architecture. A set of comprehensive requirements for a better control in design is then defined. Modeling and simulation are important in automated warehouse research. In this chapter, a simulation model is designed, two real cases studied are analyzed, many operational scenarios and strategies are discussed and analyzed, and many suggestions for improvement are discussed and evaluated to optimize the model.

The importance of simulation is that it is usually used to test and prove the results obtained from the analytical model. Automated warehouses are generally quite complex and also time-consuming. Simulation is thus perfect to identify maximum operating capacity, find potential bottlenecks and to compare alternative designs and troubleshoot problems. Simulation is widely used as a verification tool when creating designs consisting of the debug cores, and it may be helpful for functional exercises after implementation. Baker and Halim (2007) have presented a literature survey about the way computer simulation tools are used in many companies in order to support a better and more sustainable design. Khachatryan (2006) conducted a simulation using Brooks Automation‘s *AutoMod* simulation software. *AutoMod* automatically creates modules to model conveyors and ASRS and deliver statistical reports. A simulation process was constructed by Khojasteh-Ghamari and Son (2008) in order to find the most efficient time and also to obtain the required central processing unit time, however, each case was first solved by using enumeration methods.

Another simulation was conducted by Bleifuß et al. (2012) in parallel to the process steps of the Schaefer Case Picking (SCP) solution. The first stage of simulation is based upon a wheeler lift and the collecting conveyor. The second stage of simulation focuses on a detailed consideration of tray storage, especially the different heights of loaded trays. Storage regulations were then developed. The third stage of simulation was to test the impact of quality checks such as clearing processes when failure occurs during operation. The fourth stage of simulation is to support specific SCP design according to the wholesale company. The fifth stage is the material flow controller (MFC). An emulation condition was developed, and that condition has been used to evaluate the control of each subsystem of the SCP individually.

Wang et al. (2010) have demonstrated a simulation with respect to automated warehousing systems. As found in a study by Al-Zuheri (2013), a simulation modeling technique usually needs much effort and cost to find the best solution, if compared to a mathematical model. Simulation models with different degrees of accuracy are a robust technique for optimizing warehouse design. Yu (2008) used *AutoMod 10.0* to evaluate the simulation results for every specific setting involving empirical distribution for transaction time. Butdee et al. (2008) have tested control parameters using a simulation method using LABVIEW to demonstrate the algorithm of the AGV.

Using simulation, Wang et al. (2010) proved that a warehousing system can deliver a large number of items from the storage area to the assigned location. The simulation results showed minimal delay with maximum capacity of the system. Gagliardi et al. (2010) concluded that simulation is a numerical analysis technique to evaluate the differential responses of complex models.

5.2 Simulation Model, Logic and Software

The simulation model was designed according to the final layout dimensions of the applied use-case model, which was shown in Section 4.4, and the technical parameters of applied use-case model, which were discussed in detail in Section 4.5. All modules of the simulation model have the same dimensions and velocities as the use-case model's parts, and the time needed for executing any task was identified according to the specification and the time-consuming for these parts. To simulate the ACCPS and its operating principles, several picking order scenarios will be applied for SKUs that consist of one hundred types of goods related to the number of cells in the use-case model. Two scenarios related to the number of handled SKUs will be executed: the first evaluates the model when the number of handled SKUs is not more than the number of cells. The second evaluates the model when the number of handled SKUs is more than the number of cells. Two real cases were considered, and two real-time data situations were simulated, and the model performance was evaluated. Under these conditions the effect of the SKU locations in the model and the effect of customer priorities were evaluated (see Figure 5.1).

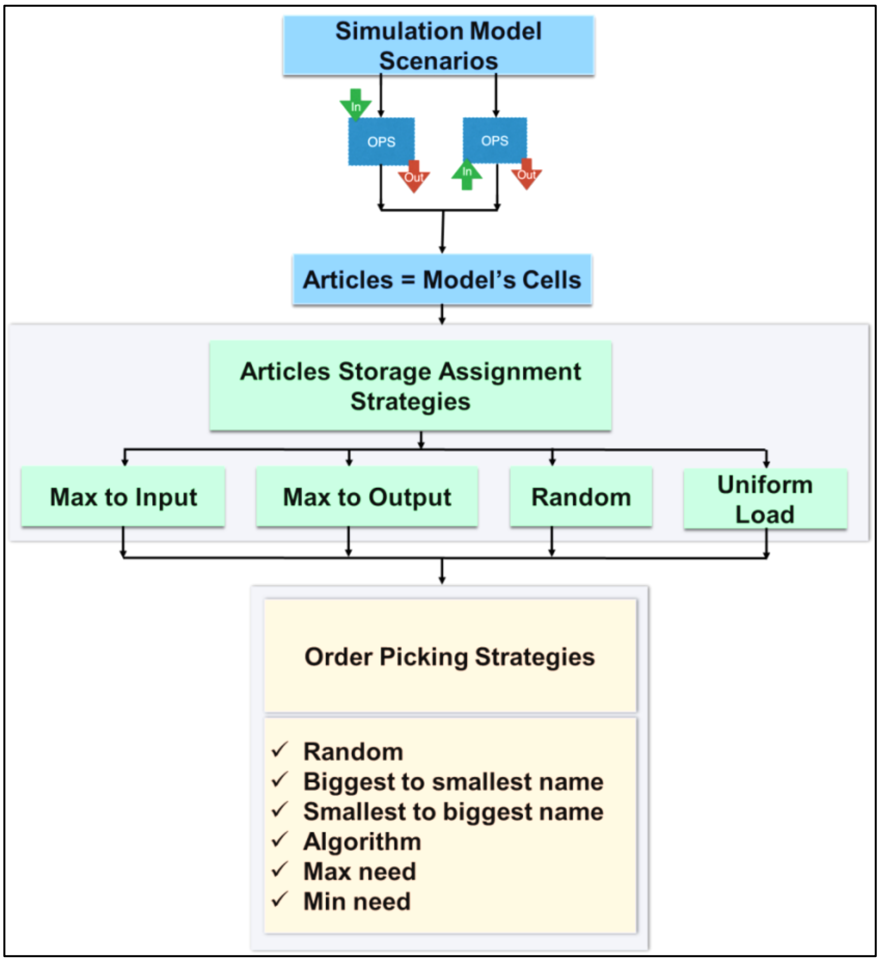


Figure 5.1 Simulation scenarios and evaluation strategies flowchart

Two kinds of input-output positioning strategies will be arranged for the scenarios, in which the input point will be on the same side, and then on the opposite side of the output point. After that, each strategy will be divided into four categories according to the article sorting strategies on the model's cells (article location in the model) as follows

Max load to the input point

The incoming order will be identified according to its required quantities from the handled articles. This required quantity of an article will be accumulated for all customers. According to the total required quantities from the handled articles, the location of every article will be identified. The article of the maximum required quantity is stored in the nearest cell from the input point (de-palletizer), and the next article of the next maximum required quantity is stored in the next nearest cell. The nearest cell to the input point is identified according to the time required to reach it from the input point (see Figure 5.2).

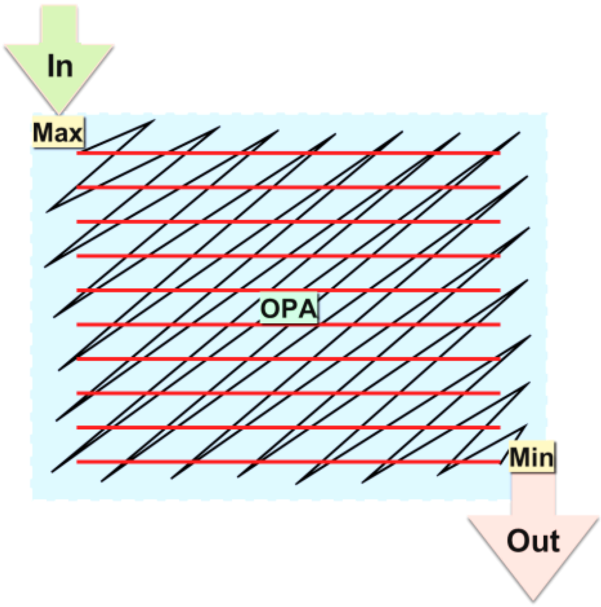


Figure 5.2 Article locations according to the strategy of maximum load to input point

The articles according to the required quantities for all customers will be distributed to the cells as the following wave design shown in Figure 5.2. The required time for an SKU to reach a cell will therefore be the deciding factor in placing the articles in the cells. The cell which has the shortest arrival time is determined to be the storage cell for the article in maximum demand. The articles are therefore distributed to the model‘s cells according to the load on them, where, the highest amount of an ordered article is placed near the entrance area as shown in Figure 5.3.

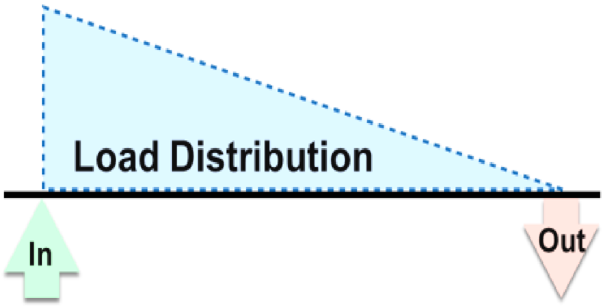


Figure 5.3 Articles distribution form in the model according to maximum load to input point strategy

Max load to the output point

Using the same principle, the article, which has the maximum required quantity, is stored in the nearest cell to the output point, and so on until reaching the last cell in the model, where the article of the minimum required quantity is stored (see Figure 5.4).

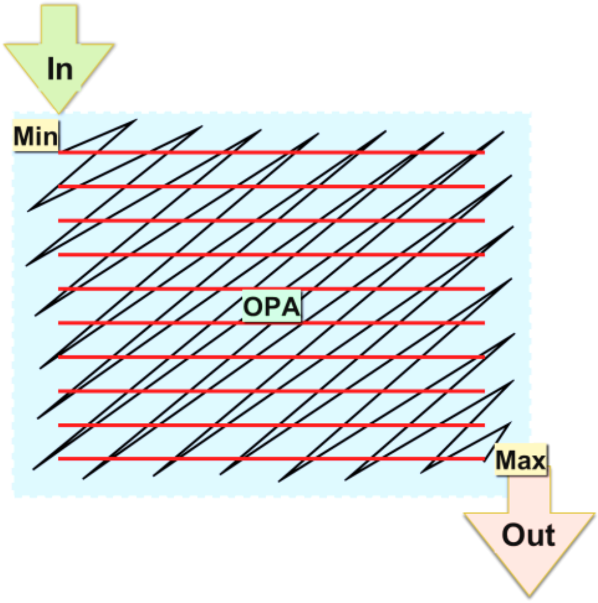


Figure 5.4 Article locations according to the strategy of maximum load to output point

The articles are distributed to the model's cells according to the load, where most ordered articles are placed in the nearest cell to the output point as shown in Figure 5.5.

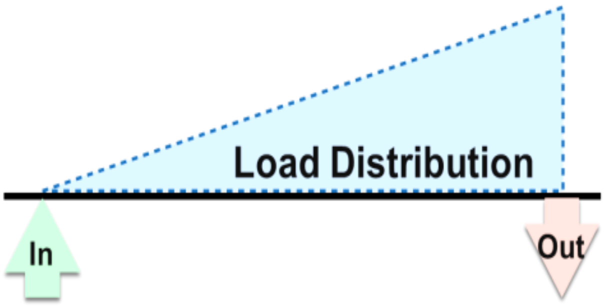


Figure 5.5 Article distribution form in the model according to maximum load to output point strategy

Random load distribution

Articles are placed in the cells randomly without considering any condition for sorting the articles in the cells. According to this strategy, the articles are distributed in the model cells randomly.

Uniform load distribution

All handled articles will be sorted according to their total required quantities. That means that they will be arranged into ten lines based on the load balance on every storage line (see Figure 5.6). The ***LP-solve*** software tool was used to arrange the hundred articles in ten groups, where every group consists of ten articles and has the same number of the total required crates. For example, if the total required amounts for the 100 articles are 50000 crates, then 5000 crates will be assigned to every line for handling. The control system sorts the articles in the model's cells in a way that makes the total load on every line as near as possible to 5000 crates. There is a possibility that one or more line will serve slightly more than 5000 and others slightly less than 5000 crates. That depends on the balancing of the article sorting process.

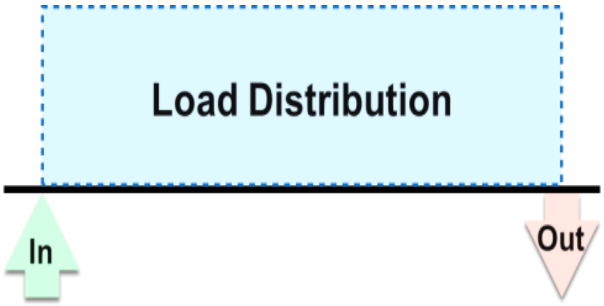


Figure 5.6 Article distribution form in the model according to uniform load distribution

Once the articles are placed in the model and all cells are full, OPP will be performed in many scenarios according to customer list priority, such as:

Random customer list

The OP list is prepared according to a random customer list. The customers will be arranged in a list randomly, and the picking process executed according to this list, customer by customer, without considering consumer priority. There is no customer classification that ensures customer service time, or the location of a customer on the picking list.

Smallest to biggest name

Each customer will be identified by a special ID-number. OPP will be executed according to the sequence of the customer number (customer list). Customers will be sorted according to their ID-numbers from the smallest ID-number to the biggest ID-number. The order will be retrieved from the system following smallest to biggest rules. For example, if there are 100 customers called customer-001 to customer-100, the first order will be processed for customer-001, and the last will be for customer-100.

Biggest to smallest name

Similar to the smallest to biggest method, only in this case, the orders will be retrieved inversely from the system starting with customer-100 and ended with customer-001 (biggest number to smallest number).

Max to min need

The customer list is arranged according to the required quantities of every customer. The customer with maximum need has the highest priority and is located first in the OP list.

Min to max need

The customer list is arranged according to the required quantities of every customer. The customer with the least need has the highest priority and is located first in the OP list.

Algorithm of arrangement customer priority list

The *Matlab* program was used to generate the picking list according to an algorithm. The customer list was arranged according to the required quantities of every customer, and the customers were arranged in a list according to an arrangement algorithm. The aim of this algorithm is to make a load balance on the lines along the time of the retrieval process for all customer orders. The logic of this algorithm is described as follows

1. Select a random customer to be the first customer in the picking list, this customer will be as the reference (starting point).
2. Find the total number of required crates for this customer from every storage line. Arrange these ten lines in a list according to the total maximum required crates. Select the line of the maximum load.
3. Find the next customer, who needs the minimum number of crates from this line.
    - If only one customer was found, select them as the next customer in the OP list. Then, repeat the algorithm from steps (2) and (3) for every new customer to the last one.
    - If two or more customers have been found who need the same minimum number of crates from this line, select the next line of the maximum load for

the previous customer (the customer of step 2) and repeat the algorithm from step (3) until one customer can be found at the end. This customer will be the next customer in the picking list. Repeat the algorithm from step (2) to find the next customer, and so on, until the last customer in the picking list.

- If repeating processes reach the last line for the previous customer (the customer of step 2), and still there are more than one customers, who have the same minimum required crates, then select any one to be the next customer in the picking list. Repeat the algorithm from step (2) to determine the next customer in the picking list, until the last customer in the picking list is determined.

For a greater understanding of how the picking list is prepared according to the algorithm of load distribution and to obtain a retrieving load balance for all storage lines, the next flowchart explains the logic of this algorithm.

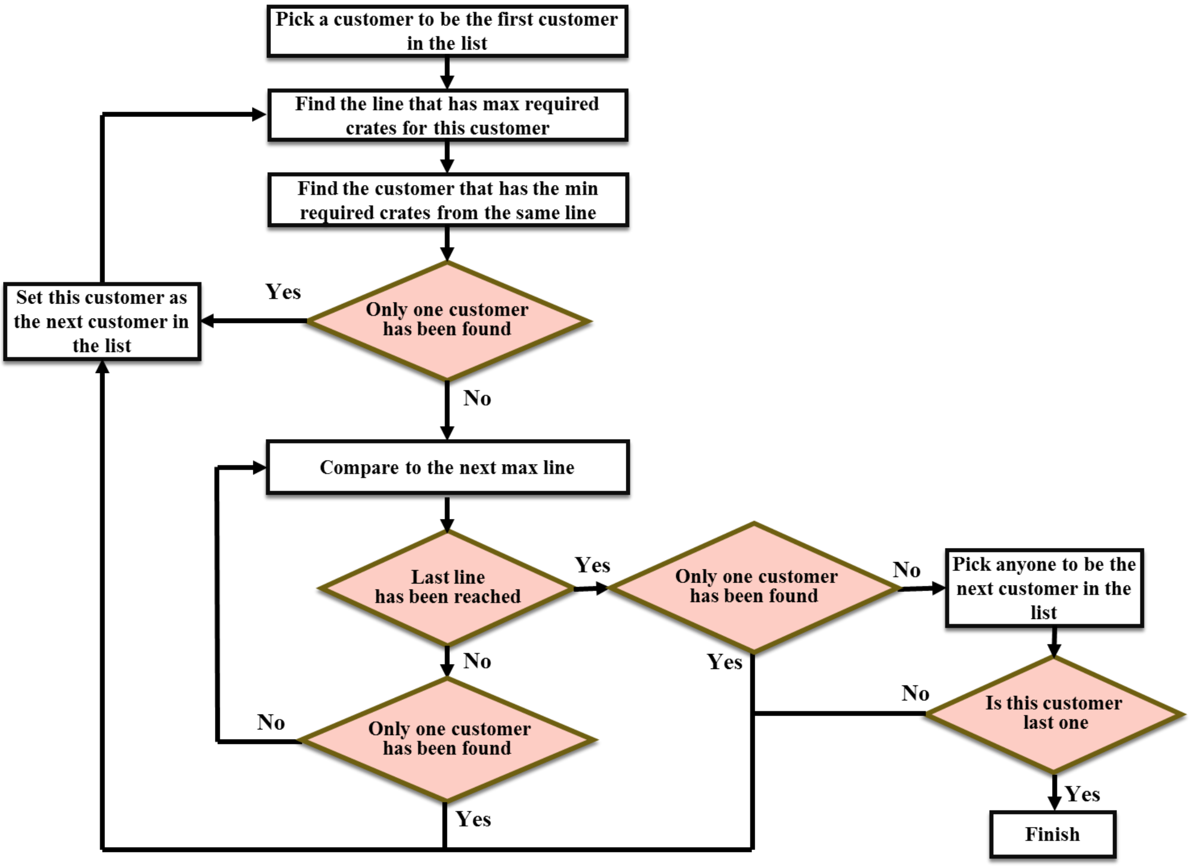


Figure 5.7 Flowchart of the customer list preparing algorithm

The discrete-event simulation toll ***"ProModel"*** was used to simulate the ACCPS use-case model. The simulation model was built to the same technical parameters as the designed ACCPS's use-case model. The layout of the ProModel simulation model was designed as in Figure 5.8.

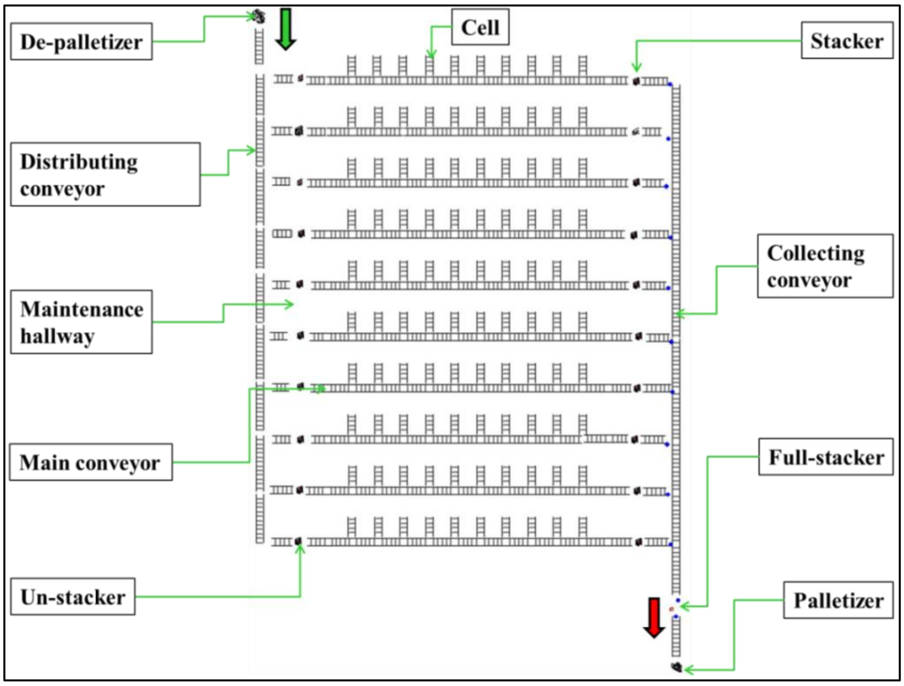


Figure 5.8 Layout of the simulation model

Real-time data for two cases was used and simulated, in order to evaluate the system under possible operating conditions. Many scenarios related to the storage assignment problem, OP strategies, material flow shapes and the optimization process were simulated. The results were analyzed and evaluated.

5.3 Simulation Scenario for Filling Process

Filling is the first stage of the OPP. All cells must be filled with articles; every cell has a capacity of 52 crates (one full pallet). The aim of this simulation scenario is to evaluate the model's performance at the first stage of the operation processes (filling stage). In this scenario, the required time for feeding the pallets into the de-palletizer was not considered. The time considered was that of de-palletizing (splitting the pallet into four stacks), transporting (on a distributing conveyor and the main conveyor), de-stacking (splitting the stacks into crates) and storing these crates in cells. 100 pallets were fed to the model. The filling process began at cell_10, which is located on storage line_1, and refers to this cell as (C1_10). The first crate reaches this cell at 37.8 seconds, and after 2.4 seconds the next crate enters the cell. The last crate enters the cell at 160.2 seconds. By omitting the first 37.8 seconds from the total (160.2), and dividing by the number of stored crates to this cell (51) in this interval of time, the average stored time per crate is determined as 2.4 seconds per crate (see Figure 5.9).

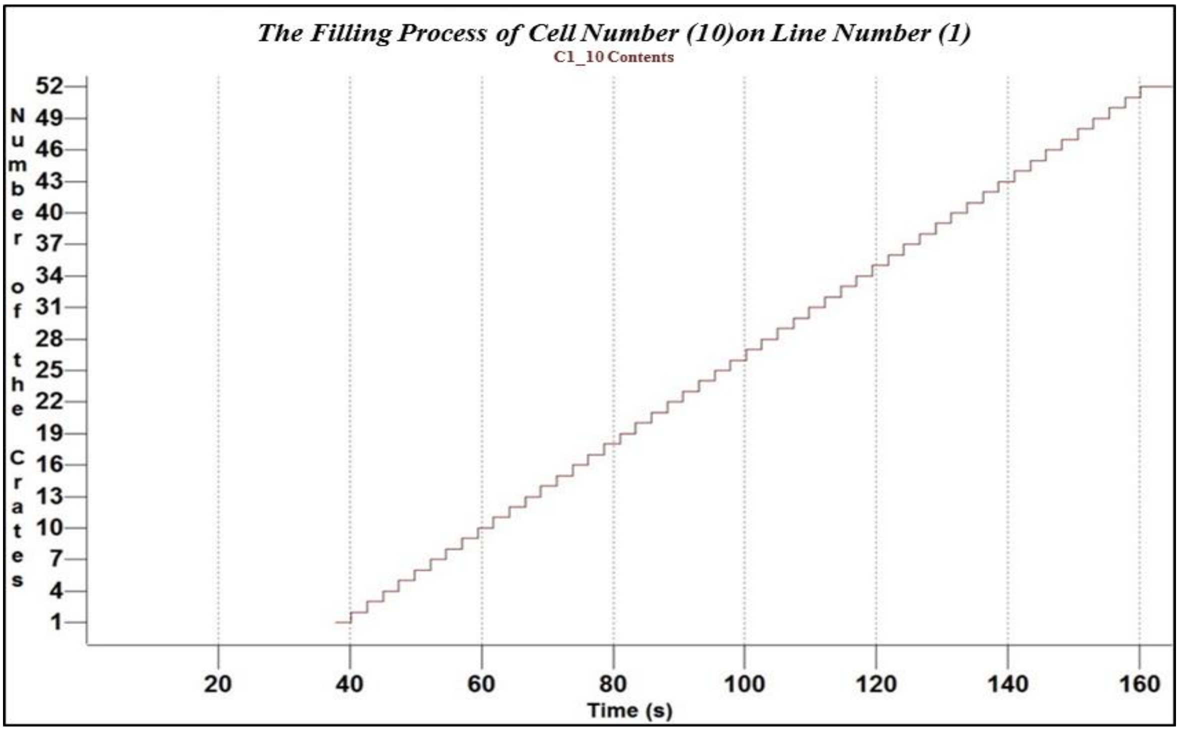


Figure 5.9 The filling process of cell_10 on storage line_1

The simulated filling process for all cells on storage line_10 can be shown as in Figure 5.10. This figure explains the filling process, and shows the changes in the number of the crates within the cells over the time. The total time of the filling process was 0.387 hours (1392.5s). The last filling process was for the cell_1 on storage line_10.

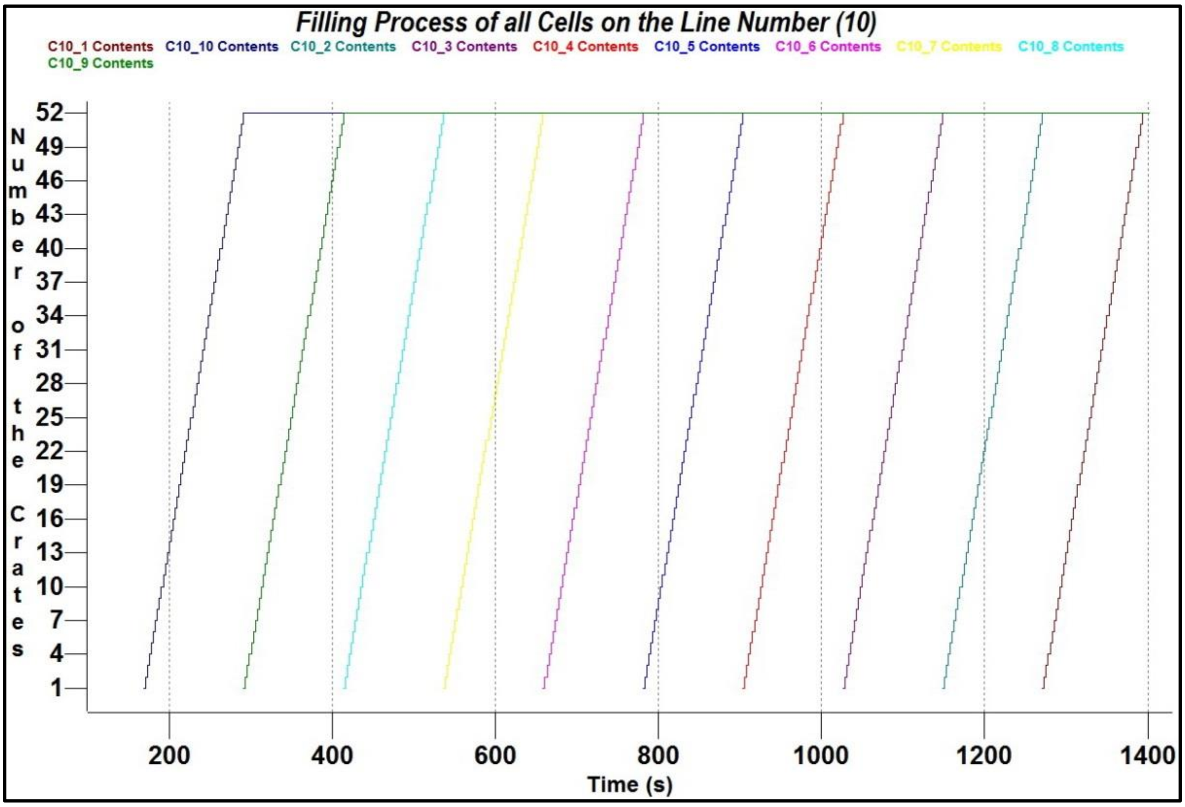


Figure 5.10 The filling process of all cells on line_10

The average throughput of the model during the filling process is determined as follows

$$Thr_{filling}^{ave} = \frac{(C^{model})}{T^{fil}} = \frac{5200}{0.387} = 13436.7\ crates/h,$$

where $Thr_{filling}^{ave}$ is the average throughput of the filling process, C^{model} is the capacity of the model, and $T^{fil}$is the filling time of the use-case model.

The state of the de-palletizer during the simulation time of the filling process was as in Figure 5.11. Operation state represents the rate of time that the location is actually processing an entity, which was 86.99%. Idle state represents the period of time when no entities are at the location, and was 13.01%. Blocked state represents the rate of time that entities spent waiting for a free destination, and was 0.00%. Theoretically, this time is the total waiting time for the stacks in the de-palletizer because of the capacity limitation or activity execution after the de-palletizer process. This waiting time is considered blocked time, and therefore the total utilization rate of the de-palletizer is 86.99% of the total time (see Figure 5.13). Setup time is the rate of time that the location spends on performing the required setup tasks in order to process an entity, and was 0.0% because the setup time is not considered in the process. Waiting time is the rate of time that the location is waiting for a resource or other entity in order to begin processing, and was 0.0%. Down time is the rate of time that the location is down (off-shift, on-break, or downtime), and was 0.0% because it is not considered in the process.

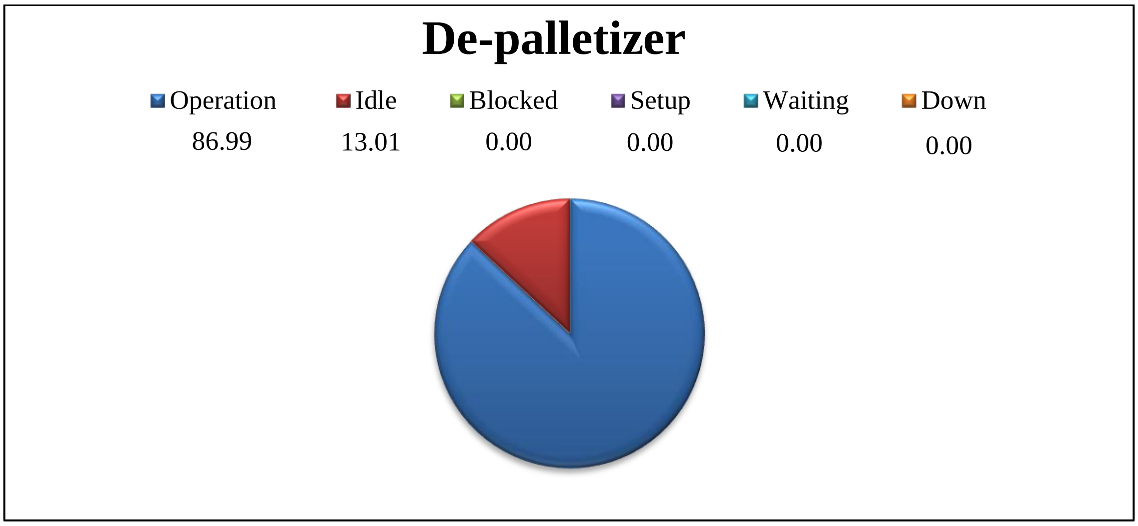


Figure 5.11 State of the de-palletizer over the filling scenario period

The state of the de-stacker is described in Figure 5.12. The rate of operation status was 88.01%, idle status was 11.99% and blocked status was 0.0%. Blockage time is the total waiting time of the crates within the de-stackers. This waiting time is considered blocked time. The operation states represent only the operating time, where no crates are blocked in the de-stackers. The total utilization rate of the de-stacker in this case therefore equals 88.01% of the total time (see Figure 5.13).

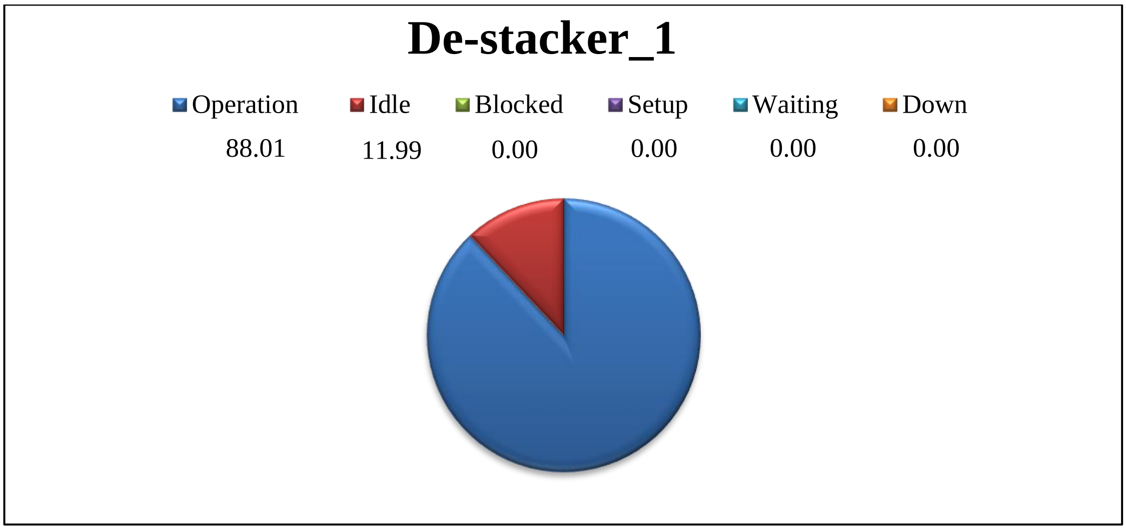


Figure 5.12 State of de-stacker_1 over the filling scenario period

The utilization of the most important locations along the entity paths in the filling scenario is summarized in Figure 5.13.

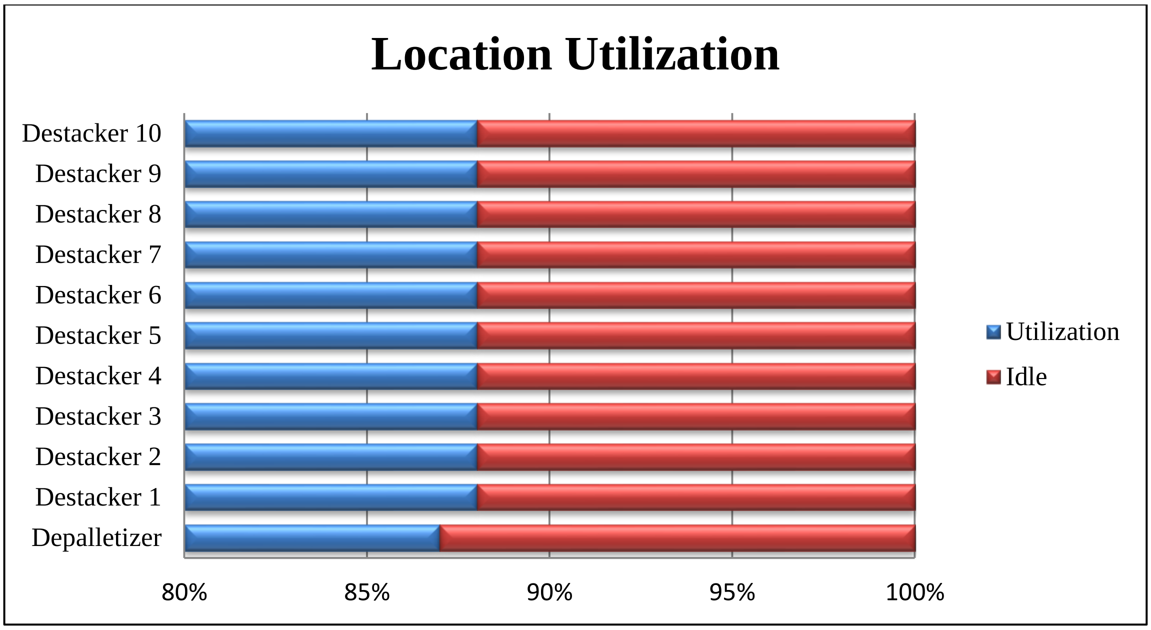


Figure 5.13 Utilization rates of the de-palletizer and the de-stacking machines over the filling scenario period

The utilization of the de-palletizer was approximately 87% and the utilization of the de-stackers was about 88%. It should be noted here that the utilization rate of the de-palletizer equals the total time of operation, and is the same for the de-stackers.

The simulation model is designed based on the principle that there is no conflict between processes, and therefore, the blocked time of the filling scenario was null. It does not mean that it was not possible for there to be a blockage state anywhere in the model, but it means that the blockage state is rare, especially in the filling stage, because it is only a storage process, there is no overlap between the processes. In the next section a blockage state might occur due to an overlap between processes, especially between the retrieval and the replenishment process. Sometimes, a blockage state occurs because of the priority of the entities, especially at the junction points, such as the junction points of the main storage lines with the collecting conveyor.

5.4 First Case Study: Number of Handled Articles Equals Number of Cells

This case involved a bakery industry plant. According to the working plan, the production starts before knowing the exact demand, depending on forecasts. During the time interval where the customer requests being received, the production plan can be rearranged according to the customer requests. The management office receives the customer requests and prepares the rearranged production list for production area and the OP list for picking area (see Figure 5.14).

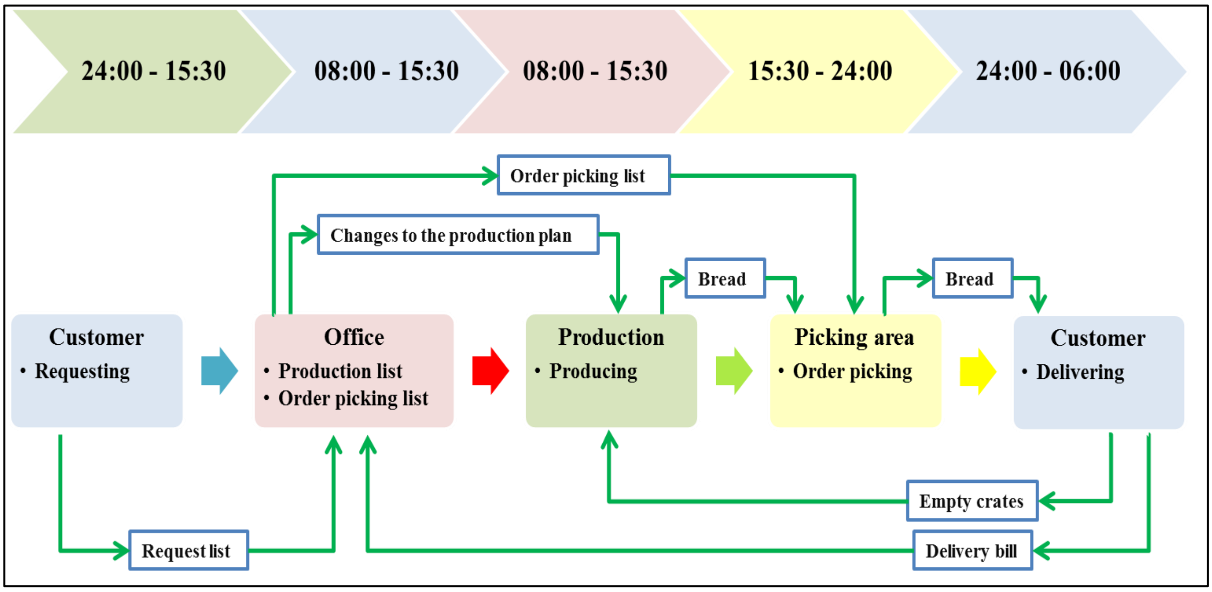


Figure 5.14 Process phases and working plan for bakery plant

Order picking time is the most important time in this process, as shown; the OPP begins at 15:30 pm and is finished at 24:00, and therefore, there are 8.5 hours to finish the OPP, and about 6 hours for delivering the products to customers. This plan is the real daily working plan of the bakery plant, where manual OPP is used in order to fulfill customer orders. Within the plant the manual OPP is based on the paper pick list system, where a paper pick list is attached to a clipboard. Paper pick lists include key information, such as item description and the quantity to pick. Pickers pencil a check mark next to the item on the paper pick list that they have picked. The item is placed onto a pallet and the process repeated until the picker has completed the customer order. Table 5.1 summarizes the logistics problems of manual OPS within this plant.

Table 5.1 Parameters of the first case study and the manual OP problem

Bakery OP problem parameters	
Number of products	100 Articles
Number of customers	675 Customers
Number of crates	45000 Boxes/day
Number of production lines	6 Production lines
Maximum plant productivity	2607 boxes /h
OPS	Manual (20 workers/shift)
OP time	8.5 hours
Working cost Euro/h	22.5 Euro/h
Working days	6 Days/week and 52 weeks/year
OP costs	Annually about 1,123,200 Euros

The simulation input parameters that were prepared according to the bakery OP problem, based on the real-time data from this plant, are summarized in Table 5.2.

Table 5.2 The initial simulation parameters of the first case study

Simulation input parameters	
Total number of products	100 Articles
Total number of customers	675 Customers
Total number of input pallets	858 Input pallets
Total number of required crates	44640 Crates
Total number of order-lines	16715 Order-lines
Order size per order-line	Max 40, min 1, average 2.67 (Crates/Order-line)
Order-lines per customer	Max 33, min 1, average 24.76 (Order-lines/Customer)
Total crates per customer	Max 140, min 1, average 66.16 (Crates/Customer)

The technical parameters of the simulation model modules of this case were determined according to the use-case model design parameters and are the same as in filling simulation model scenario. Many scenarios were applied, described in Section 5.2 and are summarized in Table 5.3. The goal of these scenarios is to evaluate the model performance under the *Storage*

Location Assignment Strategies and *OP Strategies* in order to optimize the use-case model design and the efficiency of the OPP.

Table 5.3 Simulation scenarios of the first case study

Articles = Cells ***I-shaped Flow***		***Article Location Strategies (Distribution Function of The Load)***			
		Max to input point	Max to output point	Randomly in the model	Uniformly over the lines
Order picking strategies based on customer priority	Smallest to biggest name	The article in maximum demand is stored near the input point and the customer list is prepared according to the customer names, smallest to biggest.	The article in maximum demand is stored near the output point and the customer list is prepared according to the customer names, smallest to biggest.	Articles are randomly stored in the model and the customer list is prepared according to the customer names, smallest to biggest.	Articles are uniformly stored in the lines and the customer list is prepared according to the customer names, smallest to biggest.
	Biggest to smallest name	The article in maximum demand is stored near the input point and the customer list is prepared according to the customer names, biggest to smallest.	The article in maximum demand is stored near the output point and the customer list is prepared according to the customer names, biggest to smallest.	Articles are randomly stored in the model and the customer list is prepared according to the customer names, smallest to biggest.	Articles are uniformly stored in the lines and the customer list is prepared according to the customer names, smallest to biggest.
	Random	The article in maximum demand is stored near the input point and the customer list is prepared randomly.	The article in maximum demand is stored near the output point and the customer list is prepared randomly.	Articles are randomly stored in the model and the customer list is prepared randomly.	Articles are uniformly stored in the lines and the customer list is prepared randomly.
	Max. to min. need	The article in maximum demand is stored near the input point and the customer list is prepared according to their demand, max. to min.	The article in maximum demand is stored near the output point and the customer list is prepared according to their demand, max. to min.	Articles are randomly stored in the model and the customer list is prepared according to their demand max. to min.	Articles are uniformly stored in the lines and the customer list is prepared according to their demand max. to min.

Min. to max. need	The article in maximum demand is stored near the input point and the customer list is prepared according to their demand min. to max.	The article in maximum demand is stored near the output point and the customer list is prepared according to their demand min. to max.	Articles are randomly stored in the model and the customer list is prepared according to their demand min. to Max.	Articles are uniformly stored in the lines and the customer list is prepared according to their demand min. to max.
Algorithm	The article in maximum demand is stored near the input point and the customer list is prepared according to the load distribution algorithm.	The article in maximum demand is stored near the output point and the customer list is prepared according to the load distribution algorithm.	Articles are randomly stored in the model and the customer list is prepared according to the load distribution algorithm.	Articles are uniformly stored in the lines and the customer list is prepared according to the load distribution algorithm.

Many working phases were on the way of simulation. The first was to build the simulation model considering the technical parameters of the ACCPS components. The next stage was the filling process, but, the biggest challenge was to determine the best storage assignment strategy. The next stage was to determine the best OP strategy (picking list preparing), and therefore, many scenarios were simulated under many conditions and constraints. The main important conditions were:

- The filling time was not considered,
- A new pallet is sent to a cell only if it will become empty, and
- All required pallets were prepared near the input point, where the transportation time for the pallets from the reserve area of the warehouse to the ACCPS use-case model was not considered.

In order to determine the optimal scenario, all possible simulation scenarios related to the storage location assignment problem are simulated, where every cell in the ACCPS use-case model is assigned for a specific product. All picking strategies related to the customer priority (picking list) were considered in all simulated scenarios. The two material shaped-flows were considered in all simulated scenarios, and the results of these applied scenarios are summarized in Table 5.4.

Table 5.4 Simulation times of all scenarios of the first case study

Articles = Cells		*Article Location Strategies (ALS) (Distribution Function of the Load) Simulation Time (Hour)*			
I-shaped Flow / *U-shaped Flow*		Max to input point	Max to output point	Randomly in the model	Uniformly for lines
Order picking strategies based on customer priority	Smallest to biggest name	14.11 14.95	13.18 12.51	11.18 11.16	10.26 10.19
	Biggest to Smallest name	14.17 14.99	13.21 12.50	11.24 11.24	9.80 10.24
	Random	12.45 13.13	11.83 11.10	9.54 9.42	8.72 8.99
	Max. to min. need	12.67 13.36	12.19 11.49	9.46 9.66	9.38 9.49
	Min. to max. need	12.36 13.06	11.96 11.24	9.43 9.55	9.29 9.49
	Algorithm	11.72 12.36	11.67 10.94	9.06 9.07	8.32 8.32

According to the simulation scenarios results summarized in Table 5.4, several conclusions can be summarized as follows

- The OP time is always optimized by changing the article location strategy from *max to input point* to *max to output point*, where the articles that have the maximum load (total required crates) are stored near the output point
- Random storage location assignment strategy could optimize the OP time
- The optimal scenario based on the article location strategies is the uniform distribution strategy, where the articles based on the total required crates are distributed uniformly in the cells
- Changing the OP strategy could be a way to optimize the OP time, but the optimization value may be not satisfactory
- The optimal OP strategy is reached by using the preparation algorithm of the customer list (picking list)
- The random picking strategy could be better than the other picking strategies

- Changing the layout of the ACCPS based on the two differently shaped flows of material could optimize the OP time, but, in some scenarios has a negative effect on the OP time and in others has no effect.

The optimal scenario was achieved by applying the storage location assignment strategy based on the uniform distribution of articles in the cells and the OP strategy based on the algorithm in order to prepare the picking list. These two strategies decreased the OP time by about 41% in the case of the I-shaped flow and by about 44% in the case of the U-shaped flow. Table 5.5 summarizes the effect of every strategy on OP time.

Table 5.5 The difference in time between all order picking scenarios in the first case study

Articles = Cells *I-shaped Flow* *U-shaped Flow*		*Article Location Strategies (Distribution Function of The Load)* *Difference Time (Hour)*				
		Max to Input point	Max to Output point	Randomly in the model	Uniformly for lines	**Max difference based on ALS**
Order picking strategies based on customer priority	Smallest to biggest name	14.11 14.95	-0.93/13.18 -2.44/12.51	-2.00/11.18 -1.35/11.16	-0.92/10.26 -0.97/10.19	-3.85/ -4.76/
	Biggest to Smallest name	14.17/+0.06 14.99/+0.04	-0.96/+0.03 -2.49/-0.01	-1.97/+0.06 -1.26/+0.08	-1.44/-0.46 -1.00/+0.05	-4.37/ -4.75/
	Random	12.45/-1.72 13.13/-1.86	-0.62/-1.38 -2.03/-1.40	-2.29/-1.70 -1.68/-1.82	-0.82/-1.08 -0.43/-1.25	-3.73/ -4.14/
	Max. to min. need	12.67/+0.22 13.36/+0.23	-0.48/+0.36 -1.87/+0.39	-2.73/-0.08 -1.83/+0.24	-0.08/+0.66 -0.17/+0.50	-3.29/ -3.87/
	Min. to max. need	12.36/-0.31 13.06/-0.30	-0.40/-0.23 -1.82/-0.25	-2.53/-0.03 -1.69/-0.11	-0.14/-0.09 -0.06/0.00	-3.07/ -3.57/
	Algorithm	11.72/-0.64 12.36/-0.70	-0.05/-0.29 -1.42/-0.3	-2.61/-0.37 -1.87/-0.48	-0.74/-0.97 -0.75/-1.17	-3.40/ -4.04/
	Max. difference based on OPS	/-2.45 /-2.63	/-1.54 /-1.57	/-2.18 /-2.17	/-1.94 /-1.92	

OPS is order picking strategy, and ALS is article location strategy

To evaluate the results, it must be known that the rows in this table represent the effect of the different storage assignment strategies and the columns represent the effect of the different OP strategies according to the picking list preparation strategies, where minus refers to decreasing time (saving time) and plus refers to increasing time (a negative effect). Fox example, by applying the picking strategy "*smallest to biggest name*", and applying the different strategies of the article location assignment, the effects are as follows

- For I-shaped flow, the time saved in changing the article location strategy from "*Max to input point*" to "*Max to output point*" is 0.93 hour. If the "*random*" strategy is applied, the total saved time would increase by 2 hours. Similarly, if the "*uniformly for lines*" strategy is applied, the total time saved would be increased by 0.92 hour.
- For U-shaped flow, the saved time is 2.44 hour, for "*random*" strategy about 1.35 hours, and for the "*uniformly for lines*" strategy about 0.97 an hour is added to the saved time.

The total saved time based on the article location strategies is summarized in the last column of Table 5.5, and the saved time based on the OP strategies is summarized in the last row of Table 5.5. The best scenario involved using the uniform storage assignment with the picking strategy, which is prepared by the algorithm. The best simulation picking time was 8.32 hours. According to this scenario, the average throughput of storage and retrieval processes, and the average throughput of the model are calculated as follows

$$Thr_{Storage}^{ave} = \frac{(Crates_{required}^{total} - model^{Capacity})}{Simulation\ time}, \tag{5.1}$$

$$Thr_{Retrieval}^{ave} = \frac{(Crates_{required}^{total})}{Simulation\ time}, \tag{5.2}$$

and

$$Thr_{S/R}^{ave} = \frac{(Crates_{required}^{total} - model^{Capacity}) + (Crates_{requered}^{total})}{Simulation\ time}, \tag{5.3}$$

then

$$Thr_{Storage}^{ave} = \frac{44640 - 5200}{8.32} = 4740.4\ crates/h\,,$$

$$Thr_{Retrieval}^{ave} = \frac{44640}{8.32} = 5365.4\ Crates/h\,,$$

and

$$Thr_{S/R}^{ave} = \frac{(44640 - 5200) + (44640)}{8.32} = 10105.8\ crates/h\,,$$

where $Crates_{required}^{total}$ is the total number of required crates, $Thr_{Storage}^{ave}$ is the average throughput of the storage process, $Thr_{Retrieval}^{ave}$ is the average throughput of the retrieval process, and $Thr_{S/R}^{ave}$ is the average throughput of the storage and retrieval process at the same time.

By adding the time for the filling process to the total simulation time, the total throughput of the model is calculated as follows

$$Thr_{model}^{ave} = \frac{(Crates_{required}^{total})}{Simulation\ time + filling\ time}, \tag{5.4}$$

then

$$Thr_{model}^{ave} = \frac{44640}{8.32 + 0.387} = 5126.9\ crates/h,$$

$$Thr_{Storage}^{ave} = Thr_{Retrieval}^{ave} = Thr_{model}^{ave} = 5126.9\ crates/h,$$

and

$$Thr_{S/R}^{ave} = \frac{2 * 44640}{8.32 + 0.387} = 10253.8\ crates/h,$$

where Thr_{model}^{ave} is the average throughput of the model.

The changes in the number of crates within the cells during the picking process time (in hours) are explained as illustrated in Figure 5.15.

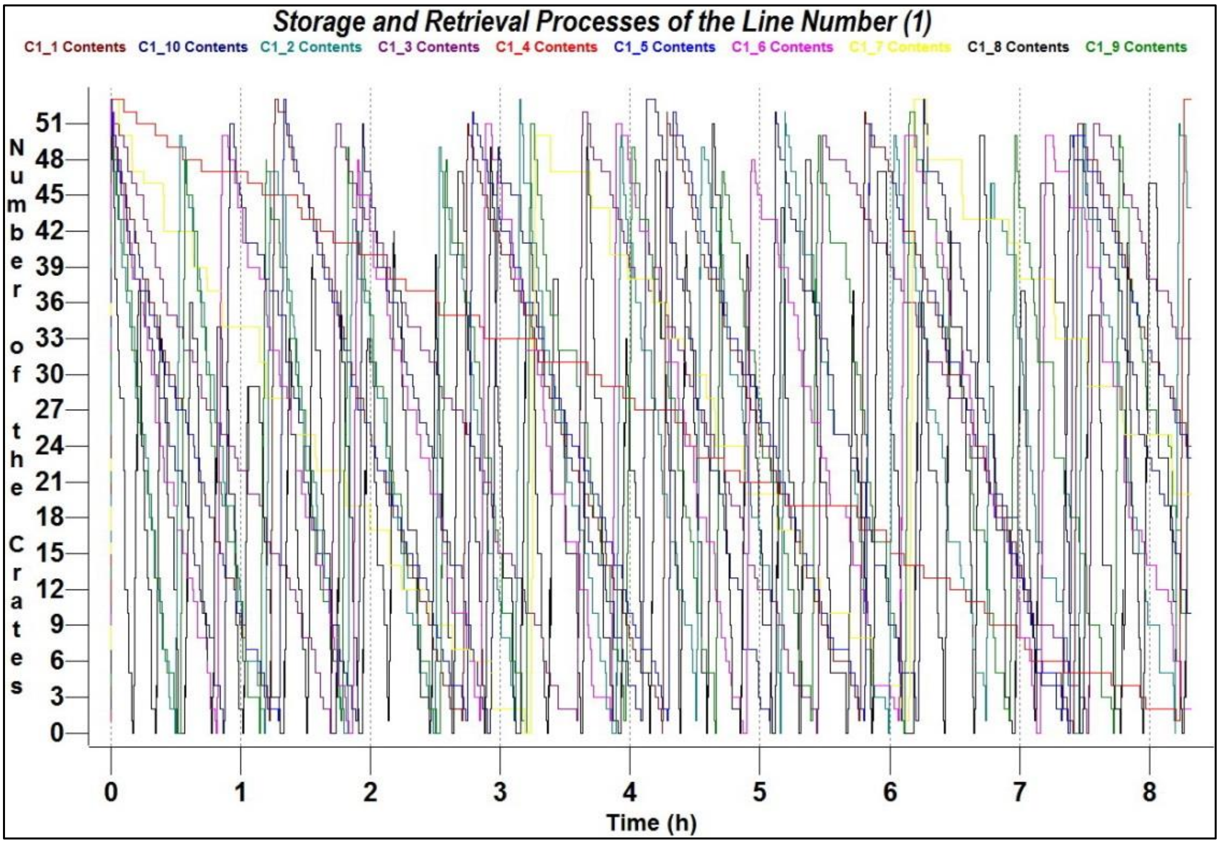


Figure 5.15 Storage and retrieval processes of all cells in storage line_1

As shown, all cells were full at time zero, and the picking process starts from every cell, but at different speeds, where the number of stored crates within these cells is decreasing. If the curve of the capacity reaches the zero point, a new full pallet of the same article is sent directly to this cell. If the new pallet reaches the cell, the capacity curve starts to rise one by one. Sometimes, not all replenished crates enter the cell, and some crates are transported directly to the outlet of the storage line, and therefore, some waves will not reach the maximum height, but will reach a height representing the total number of crates that entered the cell. The first two waves that reached the zero point on the axis of the number of the crates are for one cell. That means that the load on this cell is very high, but this may not be a steady state over the total picking time. As shown here, the minimum load was in cell_4, where the capacity curve of this cell is slowly decreasing, and there is only a replenishment process at the end of the picking process.

Based on Figure 5.15, the maximum picking load was in cell_8, and therefore, the statistics for the picking process from this cell are presented in Figure 5.16. As shown in this figure, four replenishment processes were executed every hour. The number of crates in the cell never reaches the cell's full capacity, due to the high demand for the product stored in this cell.

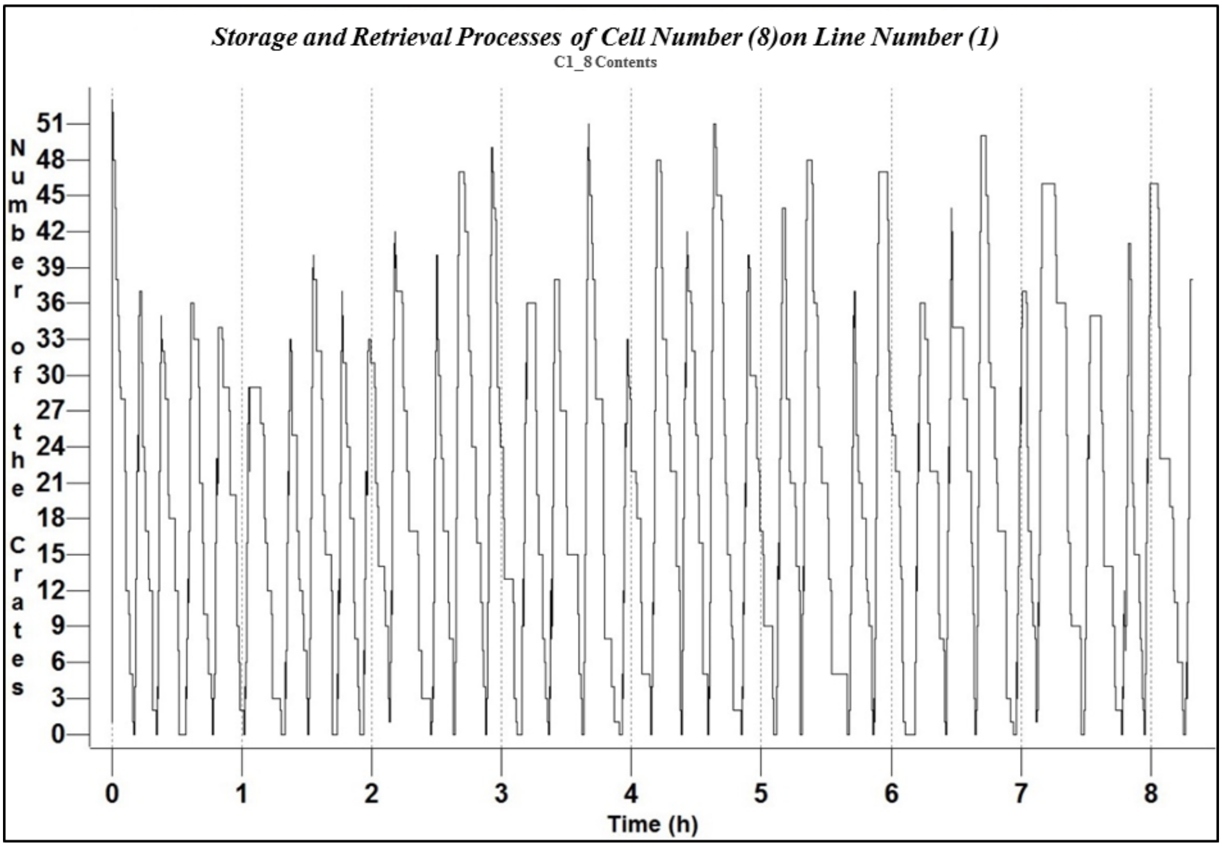


Figure 5.16 Storage and retrieval processes for cell_8 on storage line_1

The states of the de-palletizing machine and the de-stackers are shown in Figure 5.17. This figure shows the states of the de-palletizer and the de-stacking machines during the picking process in the best scenario.

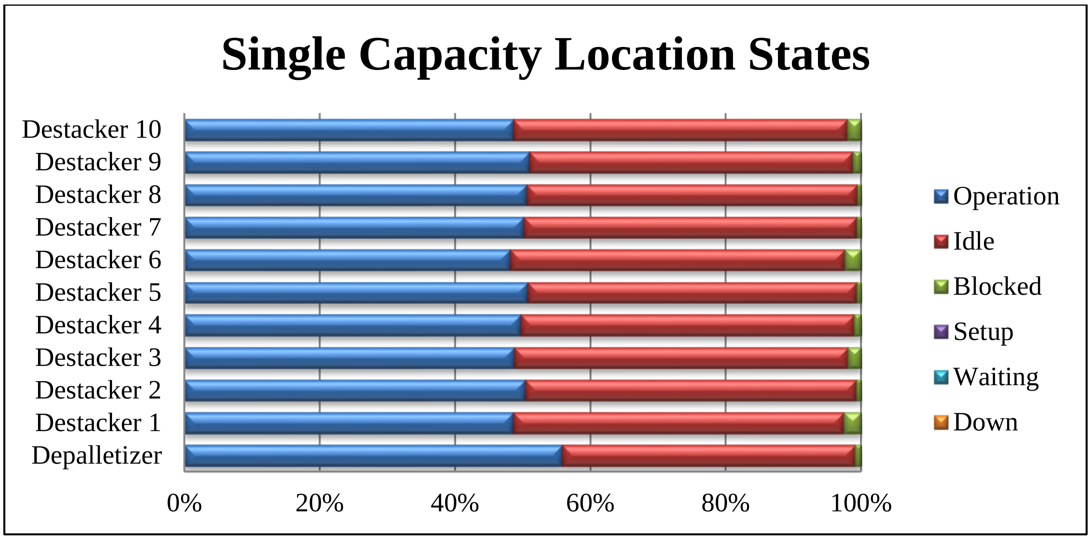


Figure 5.17 States of the de-palletizer and the de-stackers over the picking scenario period

The de-palletizer has an operating time of 56%, about 43% as idle time and about 1% as blocked time. The average operating time related to the de-stackers was about 50%, idle time was about 49% and the blocked time was about 1%. Actually, the operating time and the block time can be collected together to describe the utilization of the de-palletizer. Similarly, the blocked time of the de-stackers is referred to as the waiting time of the crates within the de-stackers, when it is impossible to leave it, and therefore, the utilization rates of these machines are determined by summing up the time of operation and blocked states. Figure 5.18 shows the de-palletizer states, where the operating time is 55.80%, idle time is 43.27% and the blocked time is 0.93%. The total utilization rate of the de-palletizer can be estimated by summing the operation and blocked times, and was 56.73% of the total simulation time.

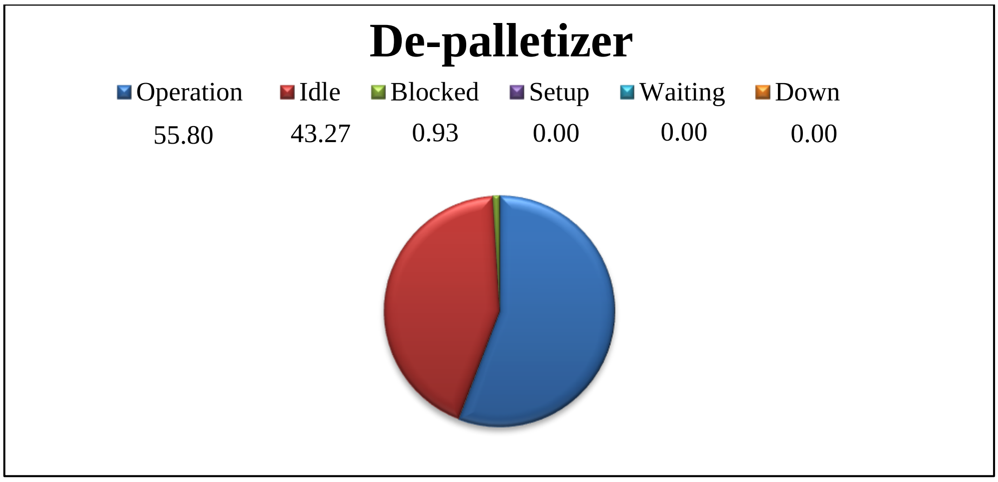


Figure 5.18 State of the de-palletizer over the best simulation scenario time

Figure 5.19 shows the state of de-stacker_10, where the operating time is 48.59%, idle time is 49.37% and the blocked time is 2.04%. The sum of the total operating time and the total blockage times equals the utilization rate of the de-stacker, and in this case was 50.63% of the total simulation time.

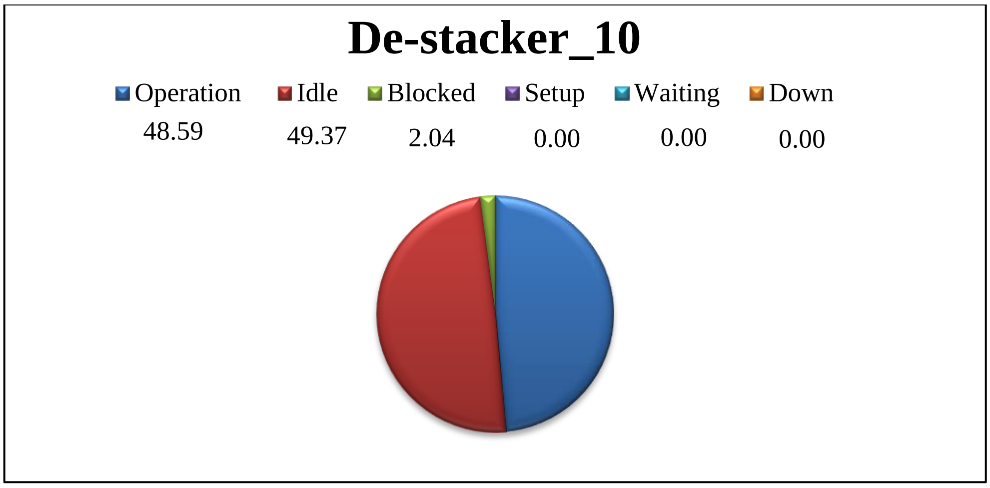


Figure 5.19 State of the de-stacker_10 the best simulation scenario

The states of the stackers during the picking scenario are described in Figure 5.20. It can be noted here that the utilization rate of the stacker is higher than the utilization rate of the de-stacker in the same line. There are two reasons for this. The first is that because the number of the stacked crates is higher than the number of de-stacked crates, where the number of crates for filling the cells is not considered. That means that the filling time is not considered here for the de-stackers. The second reason is because the number of out-going stacks from the stacker is higher than the number of the incoming stacks to the de-stacker, where stacks in the full-stack form always enter the de-stackers, but many stacks in the small-stack form may leave the stacker.

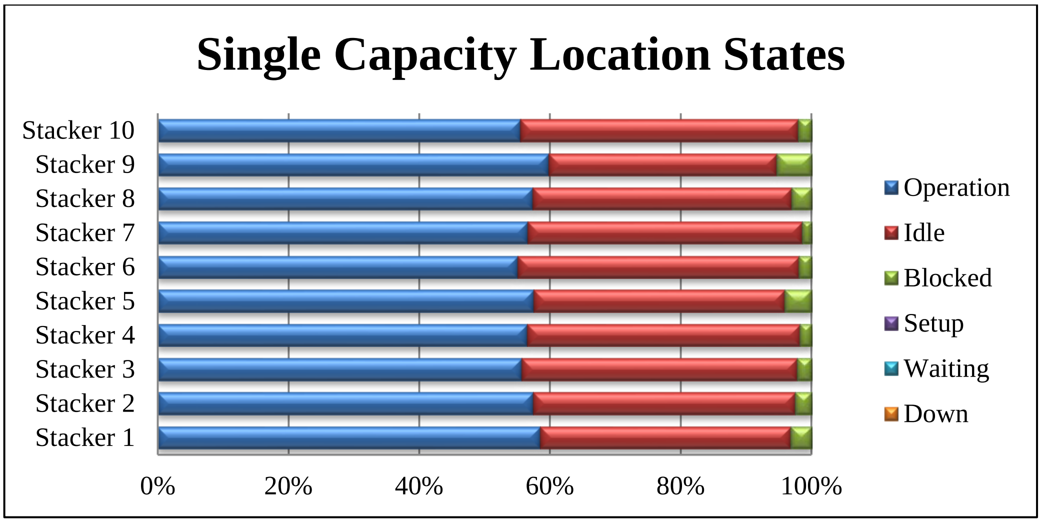


Figure 5.20 States of the stacking machines over the best simulation scenario time

As shown, the average operating time of the stackers was about 57%, average idle time was about 40% and the average blocked time was about 3%. The average utilization rate of the stackers was thus determined as about 60%.

Because the maximum load was on storage line_9, the utilization rates of the de-stacker and the stacker in this line were the maximum compared with the others. Figure 5.21 describes the state curve of stacker_9 related to the number of crates that are stacked in this time.

Figure 5.21 The state curve of stacker_9

Figure 5.22 shows a snapshot graph of the stacker_9 state curve, which is presented in Figure 5.21. Every wave represents an independent stack, and the amplitude of every wave represents the total number of crates per stack. When the wave amplitude reaches crate_13 on the y-axis, this wave represents a full-stack, and when it does not reach crate_13, this wave represents a small-stack. The first four stacks were therefore small-stacks with the number of the crates per stack 7, 8, 7 and 10, and stack_5 was a full-stack.

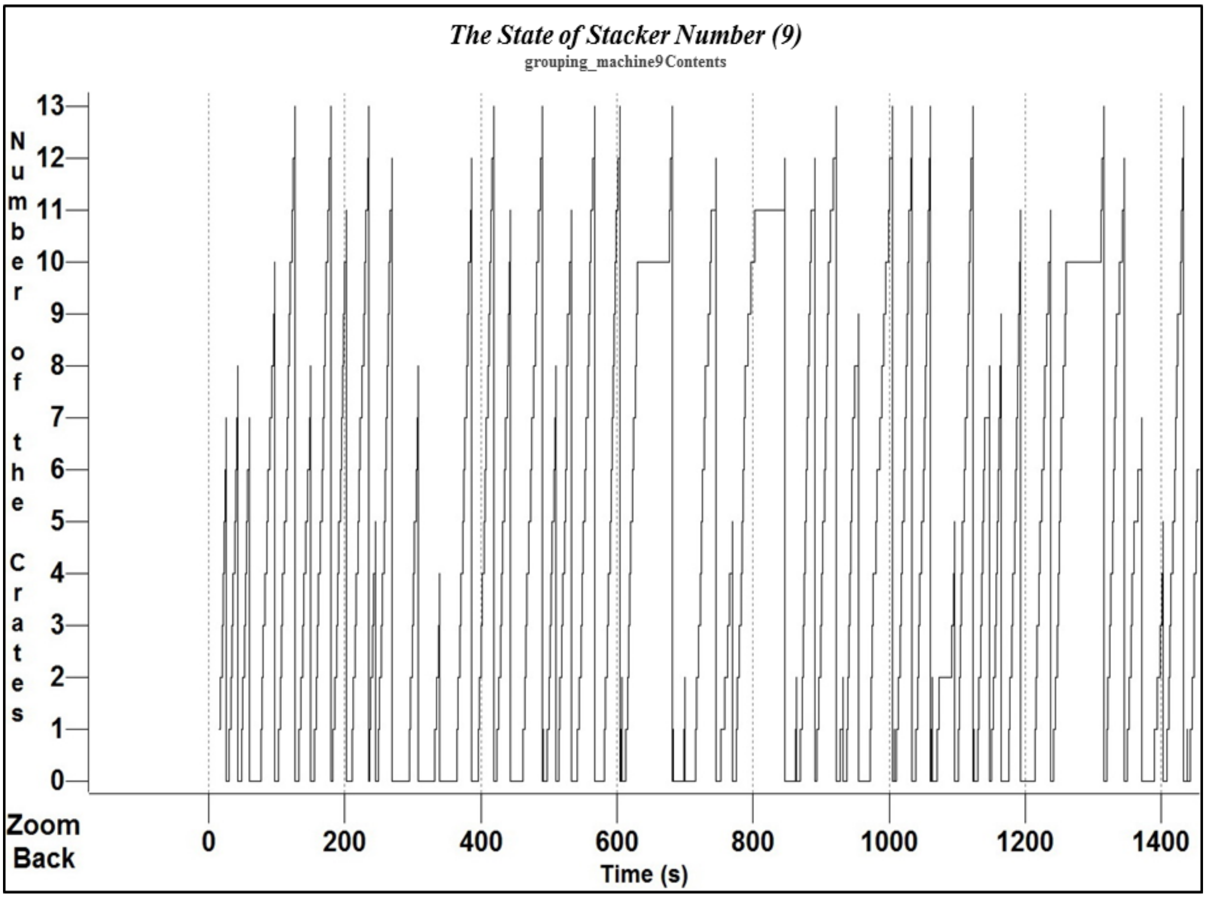


Figure 5.22 A snapshot graph of the stacker_9 state curve

Sometimes, only one crate forms a small-stack. Based on simulation results, this situation is rare (i.e. 8 times at stacker_9, and there are 237 full-stacks and 507 small-stacks with more than one crate per stack). The wavelength represents the time for the process (stacking time) plus the waiting time for the replenishment process (until the replenished crates reach the stacker).

5.4.1 Evaluation and improvements

According to the main design of the use-case model and the applied scenarios of the simulation model, the best result of the picking process time for 44640 crates was 8.707 hours with an average throughput of 5127 crates per hour. As the available time for the picking process in the real case was 8.5 hours, this was not enough to finish the picking process.

The model theoretically has the ability to reach a throughput of 15000 crates per hour, but in reality it is not possible because of the wasted time during the replenishment process for an empty cell. The idle lines problem, where there is no order requested from these lines at the time of a customer's OPP. The idle lines problem cannot usually be solved, but the effect of this problem can be decreased by considering it during storage assignment problem solving.

In analyzing this problem in order to optimize the best scenario, it is found that the customer must be waiting in the system until the new pallet reaches the cell, and then the first required crates that reach the cell can be directly transported to the output point without entering the cell. The total waiting time of the customer is affected by the time needed by the first crate of the new replenished pallet to reach the cell. This time can be minimized by either speeding up the replenishment process by increasing the conveyor velocity or by maximizing the cell capacities (adding reserve crates in every cell) to minimize the waiting time. Five new scenarios were simulated to evaluate these two suggestions for solving the problem.

The ***first scenario*** is simulated by increasing the conveyor velocities to 100%, and the ***second*** by increasing only the main conveyor velocities to 100%. The ***third scenario*** is simulated by adding ten crates to the capacity of every cell, and the ***fourth and fifth*** scenarios are integrated with the first and the second with the third scenario. This means that the capacity will be redesigned to be 62 crates per cell and the total capacity of the use-case model will be 6200 crates.

Either only the velocity of the main conveyor is changed to 1 meter per second, or the velocities of all conveyors in the system are changed to 1 meter per second. The signal for the replenishment process can be sent only when the number of crates in the cell is less than or equal to ten crates. These ten added crates will be stored in every cell only once at the beginning of the model filling process, and every new replenishment pallet will contain only 52 crates. In simulating these five scenarios, only the best previous simulation scenario was selected and developed to evaluate these optimization scenarios. The results are summarized in Table 5.6 as follows

Table 5.6 The total OP time of the optimized scenarios

Articles = Cells		***Conveyors Velocity*** ***Simulation Time (Hour)***			
		Conveyor velocity +100%	Main conveyor velocity +100%	No changes	Best scenario
Cell capacity	No changes	5.67	6.98	……..	8.32
	+ 10 crates per cell	4.62	5.89	6.92	8.32

By applying these optimization scenarios, the model throughput for every scenario can be shown in Table 5.7.

Table 5.7 The throughputs of the optimized scenarios

	Articles = Cells	***Conveyors velocity*** ***Model's Throughput (crates/h)***			
		Conveyor velocity +100%	Main conveyor velocity +100%	No changes	Best scenario
Cell capacity	No changes	7370	6059	……..	5127
	+ 10 crates per cell	8916	7112	6109	5127
	Output				
1350 pallets and 3746 stacks					

Actually, changing the velocities of conveyors to 1 meter per second, is theoretically not a problem, but in reality, it is a large technical problem, especially for the conveyor parts which are responsible for transporting stacks of crates, and so the other three scenarios are more likely to be applied. Adding ten crates to the capacity of every cell can be an expensive solution, but these extra costs can be justified due to the throughput increase. A very good solution is found by increasing only the main conveyor velocities, because this increase does not result in extra costs, and is technically possible. By applying this scenario, the total OP time and the average throughput of the model are estimated as follows

$$T_{OP}^{total} = T^{sim} + T^{fil}, \tag{5.5}$$

then

$$T_{OP}^{total} = 6.98 + 0.387 = 7.367h,$$

where T_{OP}^{total} is the total time of the OP, T^{sim} is the simulation time of the OP, and T^{fil} is the filling time of the use-case model. The average throughput of the model is determined as follows

$$Thr_{model}^{ave} = \frac{(Nr_{crates}^{total})}{T^{sim} + T^{fil}} = \frac{44640}{6.98 + 0.387} = 6059.5\ crates/h,$$

where Thr_{model}^{ave} is the average throughput of the model, and Nr_{crates}^{total} is the total number of handled crates in the model.

5.4.2 Comparison between manual OPS and ACCPS

Based on the results of the optimal simulation scenario in the first case study, an economic comparison was made between the manual picking system applied in reality and the ACCPS use-case model that could be applied. The main comparison criteria are:

***Order picking time*:** ACCPS can reduce the OP time about 1.13 hours (about 13% of the total OP time).

Operating costs: the costs of the manual OPP are about 1,123,200 Euros per year, while the operating costs of ACCPS per year are estimated as follows

$$\mathrm{ACCPS}^{\mathrm{Operating\ costs}} = \mathrm{Energy\ costs} + \mathrm{Maintenance\ costs.} \tag{5.6}$$

The total energy consumption is calculated by estimating the energy consumption per crate from the input point to the output point of the use-case model, multiplying this value by the number of handled crates per day ($Nr^{handled.cr/day}$), and then multiplying the result by the number of working days per year ($working^{days/year}$). In order to calculate the total energy cost, the total energy consumption is multiplied by the cost of one unit energy. The energy consumption of the storage and retrieval process for all required crates within the cell is calculated as follows

$$Cells.Energy_{S/R}^{cons/year} = Energy_{cycle}^{cons} * \left(2 * Nr^{handled.cr/day}\right) * working^{days/year}\ , \tag{5.7}$$

where $Energy_{cycle}^{cons}$ is the energy consumption per storage or retrieval process for one crate within the cell (this value has already been determined in section 4.5.1; it is about 0.0013KWh/cycle) and the number of working days per year is determined as follows

$$working^{days/year} = 6days * \frac{52weeks}{year} = 312\ working\ days/year\ , \tag{5.8}$$

then

$$\mathrm{Cells.Energy}_{\mathrm{S/R}}^{\mathrm{cons/year}} = 36211.9\ \mathrm{KWh/year}\ ,$$

and the total cost of the energy consumed by the cells in one year is calculated by multiplying the cell's energy consumption in one year by the cost of one kWh (in Germany about 0.21 Euro/kWh) as follows

$$costs.Cells.Energy_{S/R}^{cons/year} = 7604.5\ Euros/year\ .$$

In the worst case scenario, the same energy consumption was assumed for de-stacking and stacking machines, because they have the same operating principle. The same energy consumption was assumed for the de-palletizer, re-stacker (full-stacker), palletizer, and conveyors, and then the total energy consumption costs were calculated as follows

$$total.costs.Energy^{cons/year} = 7 * 7604.5\ Euros/year = 53231.5 Euros/year.$$

The maintenance costs were estimated by summing up the costs of expected required spare parts per year to the expected required worker costs per year. By assuming that only one worker is required per year and the total cost of spare parts per year are about 20,000 Euros, the total expected maintenance cost per year is calculated as follows

$$Maintenance\ costs = manpower^{costs/year} + Spare.parts^{coste/year}\ . \tag{5.9}$$

where

$$manpower^{\frac{costs}{year}} = 22.5\frac{Euros}{h} * 8\frac{Hours}{day} * 6\frac{Days}{week} * 52\frac{Week}{year} = 56160\ Euros/year\ ,$$

then

$$Maintenance\ costs = 56160 + 20000 = 76160\ Euros/year\ .$$

The annual operating costs of the ACCPS, where the average handled crates is about 44,640 crates per day, is determined as

$$ACCPS^{Operating\ costs} = 53231.5\frac{Euros}{year} + 76160\frac{Euros}{year} = 129391.5\ Euros/year.$$

The total annual operating costs saving achieved by replacing the manual picking system with the ACCPS is thus determined as follows

$$Annual^{saving\ costs} = Manual^{Operating\ costs} - ACCPS^{Operating\ costs}.$$

Compared to the annual operating costs of the manual system, the ACCPS can decrease the annual operating costs about 88%. The operating costs saved per year are about 993,808 Euros, however, ACCPS costs are about 2,822,528 Euros. These saved operating costs can be achieved only after repayment of the initial ACCPS costs, and therefore, the ROI time (Payback time) must be calculated as follows

$$Payback\ time = \frac{ACCPS^{costs}}{Annual^{saving\ costs}} = \frac{2822528}{993808} = 2.84\ years\ .$$

As a result, after 2.84 years the user will receive the costs of the ACCPS back, and then, every year about 993,808 Euros can be saved from the operating costs. Actually, the total saved costs from one year to another will decrease due to the increasing maintenance costs.

According to Bundesministerium der Finanzen (2000) "AFA-Tables (2000)", the useful life of most ACCPS components, such as elevators, roller conveyors, de-palletizer/palletizers, and de-stacker/stackers, is determined as 14 years, and therefore, the depreciation rate and the depreciation expense of the ACCPS use-case model per year are calculated as follows

$$D_R = \frac{100\ \%}{useful\ life}$$

and

$$D_{Exp} = D_R * (ACCPS^{costs} - Expected\ salvage\ value),$$

where D_R is the depreciation rate, D_{Exp} is the depreciation expense per year, and $Expected\ Salvage\ Value$ is the expected sale price of the ACCPS as a used system after its useful life period.

The D_R of the ACCPS use-case model is thus equal to 7.14% and D_{Exp} per year is 201,528 Euros per year if the expected salvage value is equal to zero. In order to calculate the interest rate of the investment, if the principal amount remains constant over the invested time, the following simple formula is used:

$$I\ =\ C\ x\ R\ x\ T,$$

where I is the interest money, C is the investment amount (capital), R is the interest rate per year, and T is the period of the investment.

According to the *European Central Bank,* the loan interest rate to non-financial corporations over five years in Germany at the end of August was about 2.84%, and therefore, the total interest money (I) in 14 years will be 1,122,237 Euros.

If the calculation is made based on paying back a fixed amount periodically, the payment every year is calculated as follows

$$P = \frac{R\,(PV)}{1-(1+R)^{-T}},$$

where P is the payment per year, PV is the present value.

The payment in the first year will thus be about 247,150 Euros, the total of 14 payments will be about 3,460,111 Euros, and the total interest will be about 637,583 Euros. The interest and payment every year is explained as in Table 5.8.

Table 5.8 The interest and payment value every year over the invested time

	Beginning Balance	Interest	Principal	End Balance
1	€2,822,528.00	€80,159.80	€166,990.99	€2,655,537.01
2	€2,655,537.01	€75,417.25	€171,733.54	€2,483,803.47
3	€2,483,803.47	€70,540.02	€176,610.77	€2,307,192.70
4	€2,307,192.70	€65,524.27	€181,626.52	€2,125,566.18
5	€2,125,566.18	€60,366.08	€186,784.71	€1,938,781.47
6	€1,938,781.47	€55,061.39	€192,089.40	€1,746,692.07
7	€1,746,692.07	€49,606.05	€197,544.73	€1,549,147.34
8	€1,549,147.34	€43,995.78	€203,155.00	€1,345,992.33
9	€1,345,992.33	€38,226.18	€208,924.61	€1,137,067.73
10	€1,137,067.73	€32,292.72	€214,858.07	€922,209.66
11	€922,209.66	€26,190.75	€220,960.04	€701,249.63
12	€701,249.63	€19,915.49	€227,235.30	€474,014.33
13	€474,014.33	€13,462.01	€233,688.78	€240,325.54
14	€240,325.54	€6,825.25	€240,325.54	-€0.00

If the costs of the ACCPS are financed by a loan, the total expected profit per year will therefore be about 746,658 and the total expected profit in 14 years will be about 10.45 million Euros.

5.5 Second Case Study: Number of Handled Articles Is More than Number of Cells

This case study involves the automated full-crate OPS of a DC for fresh fruit, vegetables and meat products. This case is more complex than the previous one due to the higher number of handled products, which must be stored in two temperature zones (+3°C and +12°C). There are about 171 different articles of meat products with an average daily demand of 11727 crates and about 118 different articles of fresh fruit and vegetables average daily demands of 16940 crates that must be picked. Some 58 customers have about 10480 order-lines on average per day, with an average of 2.7 crates per order-line. Table 5.9 summarizes these case problem parameters.

Table 5.9 The parameters of the second case study problem

Fresh fruit, vegetable and meat product distribution center			
	12°	*3°*	*Total*
Number of products (articles)	118	171	289
Number of customers (customers)	58	58	58
Number of crates (crates/day)	16940	11727	28667
Order-lines (positions)	5432	4048	10380
Crates per order-line (crates/position)	3.1	2.3	2.7
Receiving products (pallets)	326	226	552
Crates per pallet (crates/pallet)	52	52	52
OP time (hours)	…	…	6

The simulation input parameters are summarized as in Table 5.10.

Table 5.10 The initial simulation parameters of the second case study

Simulation input parameters	
Total number of products	289 Articles
Total number of customers	58 Customers
Total number of input pallets	552 Input Pallets
Total number of required crates	28667 Crates
Total number of order-lines	10380 Order-lines
Order size per order-line	Max. 30, min. 1, average 2.7 (crates/order-line)
Order-lines per customer	Max. 283, min. 85, average 180.7 (order-lines/customer)
Total crates per customer	Max. 761, min. 254, average 494.2 (crates/customer)

The simulation model was designed according to the technical parameters of the real case. The time for preparing and transporting pallets before and after the ACCPS was not considered. The filling time was considered according to the previous filling simulation scenario results. Due to the large number of handled articles, simulating all OP strategies and articles storage assignment strategies was not possible, and therefore, the problem solving strategy was divided into three stages:

- Stage one: classifying the handled articles into two classes according to the temperature storage degree.
- Stage two: arranging the articles according to the total number of required crates, and then dividing every class into two groups. The first group has 100 articles and the second has the other articles in this class. That means, Class 3° includes 171 articles, where these articles are divided into two groups, the first with 100 and the second with 71 articles. Similarly, Class 12° has 118 articles, they are divided into two groups, the first with 100 articles and the second with 18 articles.
- Stage three: the simulation strategy involved simulating the OPP for the first 100 articles, and then the next 100 articles. The rest of the articles for every class were simulated in one picking cycle with 89 articles, or in two separate picking cycles, one for 71 articles and one for 18 articles.

The picking cycles are simulated as a continuous picking process, where if any article is completely picked in the first cycle, a new article from the next picking cycle immediately takes its place (its cell), and therefore, there is no any waiting or refilling time between the picking cycles. Some customers must stay in the system until the last cycle is finished, however, and this might require more areas and efforts in repackaging customer pallets.

Nevertheless, the productivity of ACCPS can justify the secondary problems and the customers could perhaps be classified based on their required articles in groups, where every group of customers is assigned to a picking cycle, and it is not a problem that a customer may be in one or in more groups. Uniform load distribution strategy is used in order to solve the storage location assignment problem, where the location of every article (the location of the cell) within the use-case model is determined.

Figure 2.23 illustrates the total number of required crates per cell or per article location within the use-case model, where the cells are numbered from 1 to 100 from the first cell on the first line on the input side. The maximum load was about 438 crates per cell, in cell_2 on the line_6 (cell62). The minimum load was about 163 crates per cell, and it was in cell_5 on the line_5 (cell55), however, the average was about 286.67 crates per cell.

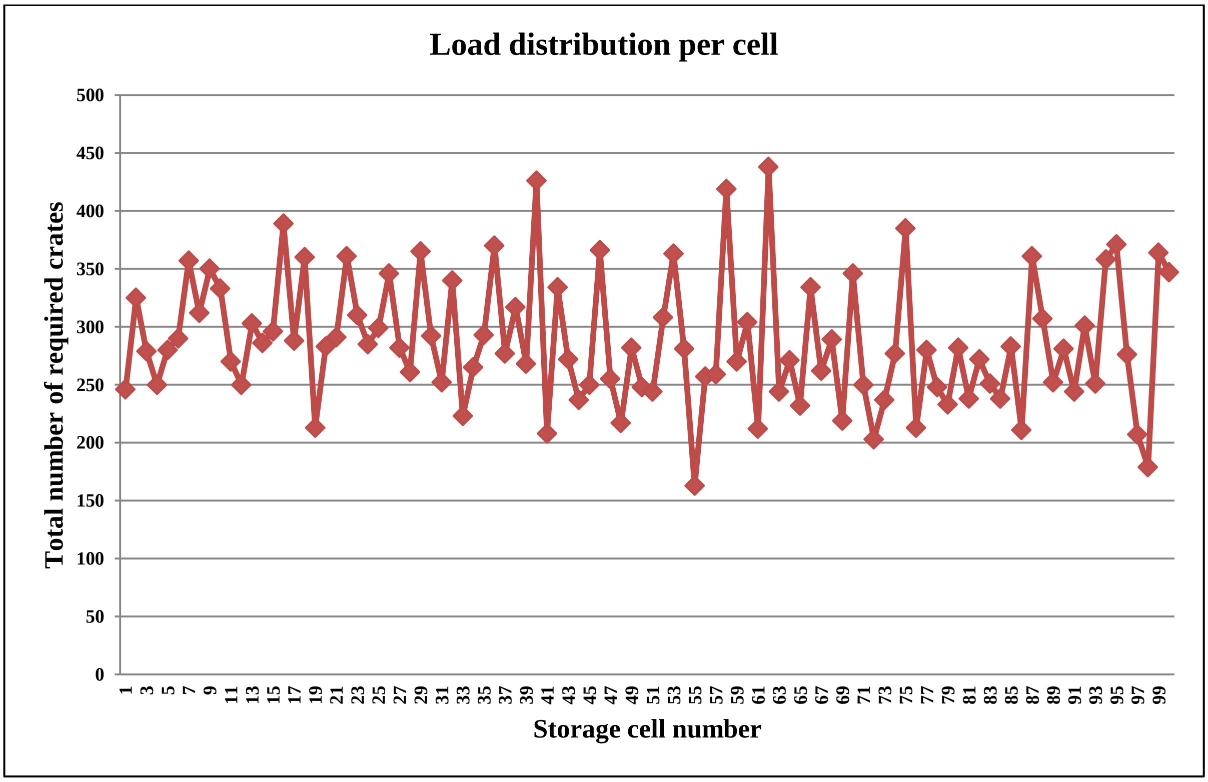


Figure 2.23 Storage location assignment based on the load distribution strategy per cell

Similarly, Figure 2.24 illustrates the total load for every storage line, where the maximum load was on line_3 with the total number of required crates around 3092, the minimum load was in line_8 with the total number of required crates about 2608, and the average number of the total required crates per line was about 2866.7 crates.

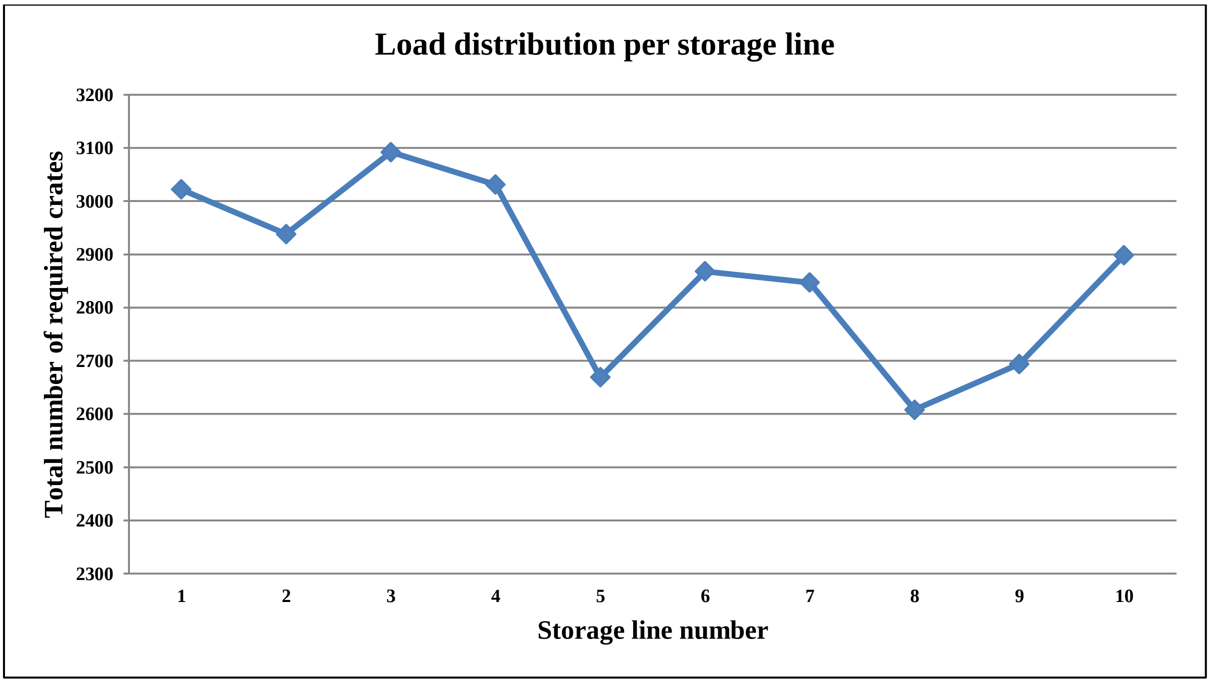


Figure 2.24 Storage location assignment based on the load distribution strategy per storage line

The picking list (customer list) is prepared based on the algorithm used in the first case study, where the customer priority was determined based on the picking load per line over the picking time.

5.5.1 First scenario: four cycles to finish the OPP

The storage location assignment problem is solved based on the uniform load distribution strategy in every picking cycle, where the articles are sorted and distributed in the cells based on the total number of required crates for every article (see Figure 5.25). In picking cycles number 3 and 4, only the required cells are operated, where the number of the required articles is less than the number of the storage cells in every cycle.

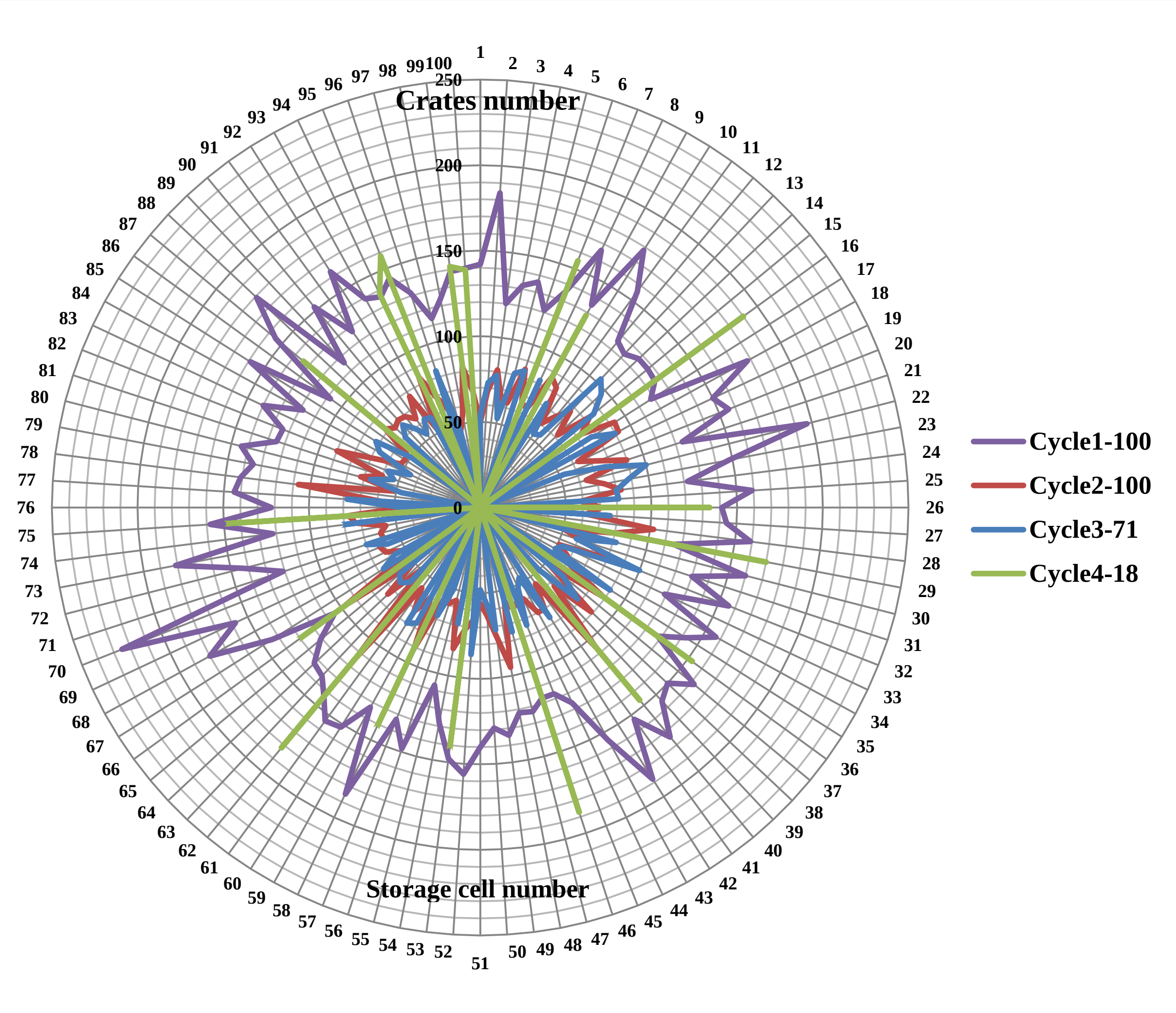


Figure 5.25 Load distributions of the articles in the storage cells in four picking cycles

Based on the customer requirements, two output pallets forms were tested. In the first the number of crates per full-stack is 13, and in the second the number of crates per a full-stack is 6. The simulation scenario is only begun when all cells are full. In this regard, the simulation time was 4.38 hours for the output pallet form with 13 crates per stack, and 4.67 hours for the form with 6 crates per stack. The total simulation time is estimated by adding the filling time to the simulation time in these scenarios, and therefore, the results of these simulation scenarios are summarized in Table 5.11.

Table 5.11 Results of the simulation scenarios in case of 4-cycles

Simulation output parameters based on output pallet forms		
	13crates/stack	*6crates/stack*
Total number of products (Articles)	289	289
Total number of customers (Customers)	58	58
Total number of output pallets (Pallets-stacks per pallet)	650 (499-4, 56-3, 49-2and 46-1)	1298 (1132-4, 62-3, 51-2 and 53-1)
Total number of output crates (Crates)	28667	28667
Total number of stacks (Stacks)	2308	4869
Simulation time (Hours)	4.38	4.67
Total simulation time (Hours)	4.76	5.05
Average model throughput (crates/h)	6014	5669
Average de-palletizer utilization	48%	45%
Average de-stacking machine utilization	45%	42 %
Average stacking machine utilization	54%	56 %
Average full-stacking machine utilization	80%	73%
Average palletizer utilization	52%	96%

By changing the stacking configuration from 13crates/stack to 6crates/stack the total picking time will increase about 6%. The number of the output pallets and the output stacks will double in the case of 6 crates per stack. The utilization of the Palletizer will double. Because of the increase in the total picking time, the utilization rates of the de-stacking machines will decrease by a lower grade. Similarly, the utilization rate of the de-Palletizer decreased up to 3%, however, the utilization rate of the stackers increased up to 2% based on the high number of the output stacks. The utilization rate of the full-stacker decreased up to 7% based on the lower number of stacks that needed a re-stacking process. The total OP time and the average model throughput for the form of 13 crates per stack were estimated as follows

$$OPT^{total} = Simulation\ time + filling\ time = 4.38 + 0.387 = 4.767h\,.$$

Then,

$$Thr_{model}^{ave} = \frac{(Crates_{required}^{total})}{Simulation\ time + filling\ time} = \frac{28667}{4.38 + 0.387} = 6014 crates/h\ .$$

The changes in the number of crates within cells during the picking process time (in hours) are explained as in Figure 5.26, where the changes to all cells on storage line_1 are shown.

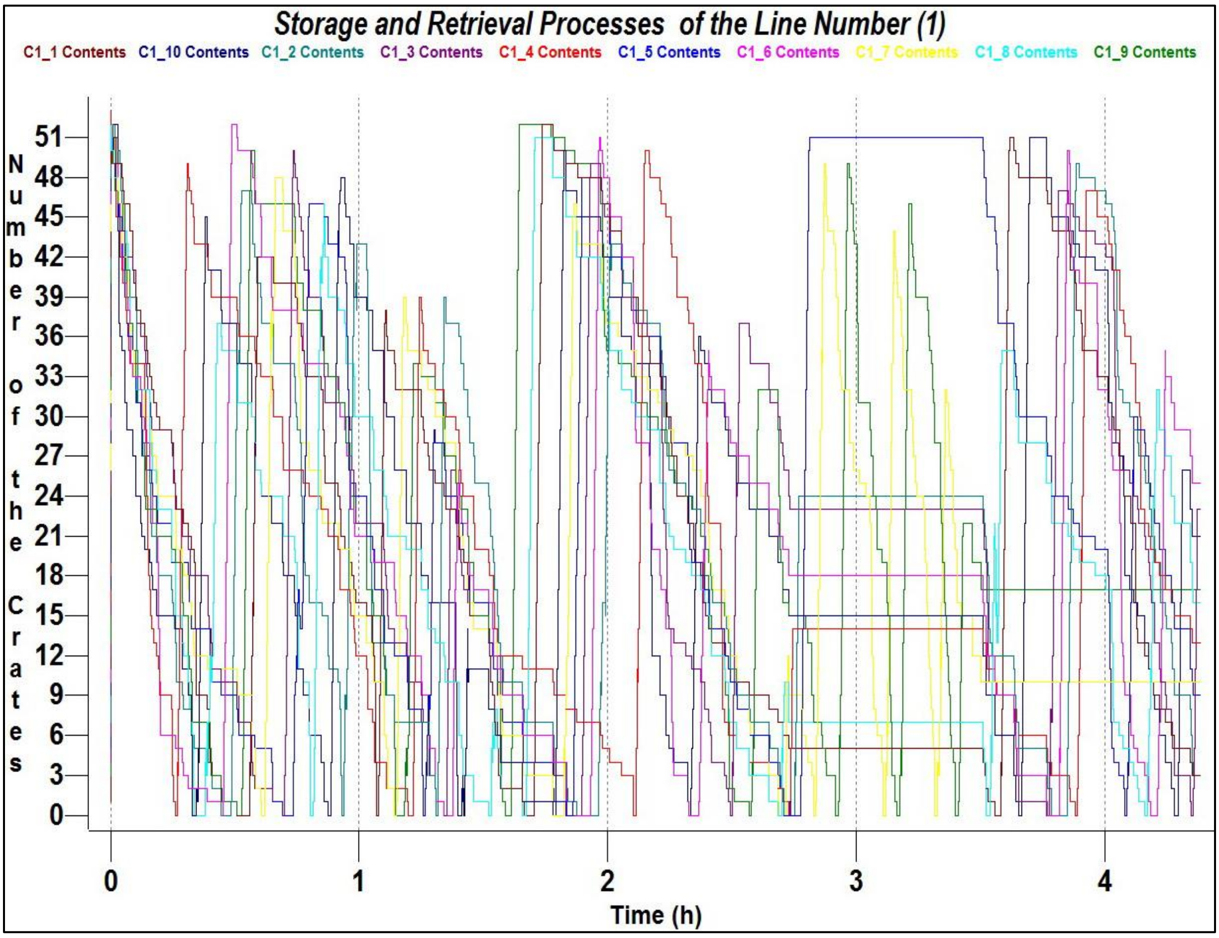


Figure 5.26 Storage and retrieval processes of all cells on line_1

At the beginning of the OPP, crates were retrieved from all cells, but at a different pace, where the first replenishment process was for cell_4, and all cells had at least one replenishment process in the first hour of the operation. Directly before the second hour of operation, all cells undergo a replenishment process sequentially, except for cell_4 whose replenishment process was after the second operating hour. Approximately, in the interval 20 minutes before and 30 minutes after the third operating hour, all cells have an idle state except cell_7 and cell_9.

For the scenario with 13crates/stack, the state of all machines in the system can be explained as in Figure 5.27. As shown, the operation rate of the de-palletizer was about 42%, the rate of the idle state was about 52% and the blockage rate was about 6%. The average operating time for the de-stacking machines was about 42%, the average idle time was about 55% and the average blockage rate was about 3%. For the stacking machines the average rate was about 50% as operating, 46% as idle and 4% as blocked. The rate of operation of the full-stacker was about 80% and about 20% in idle state. The palletizer operating time was about 52% and the idle time was about 48%.

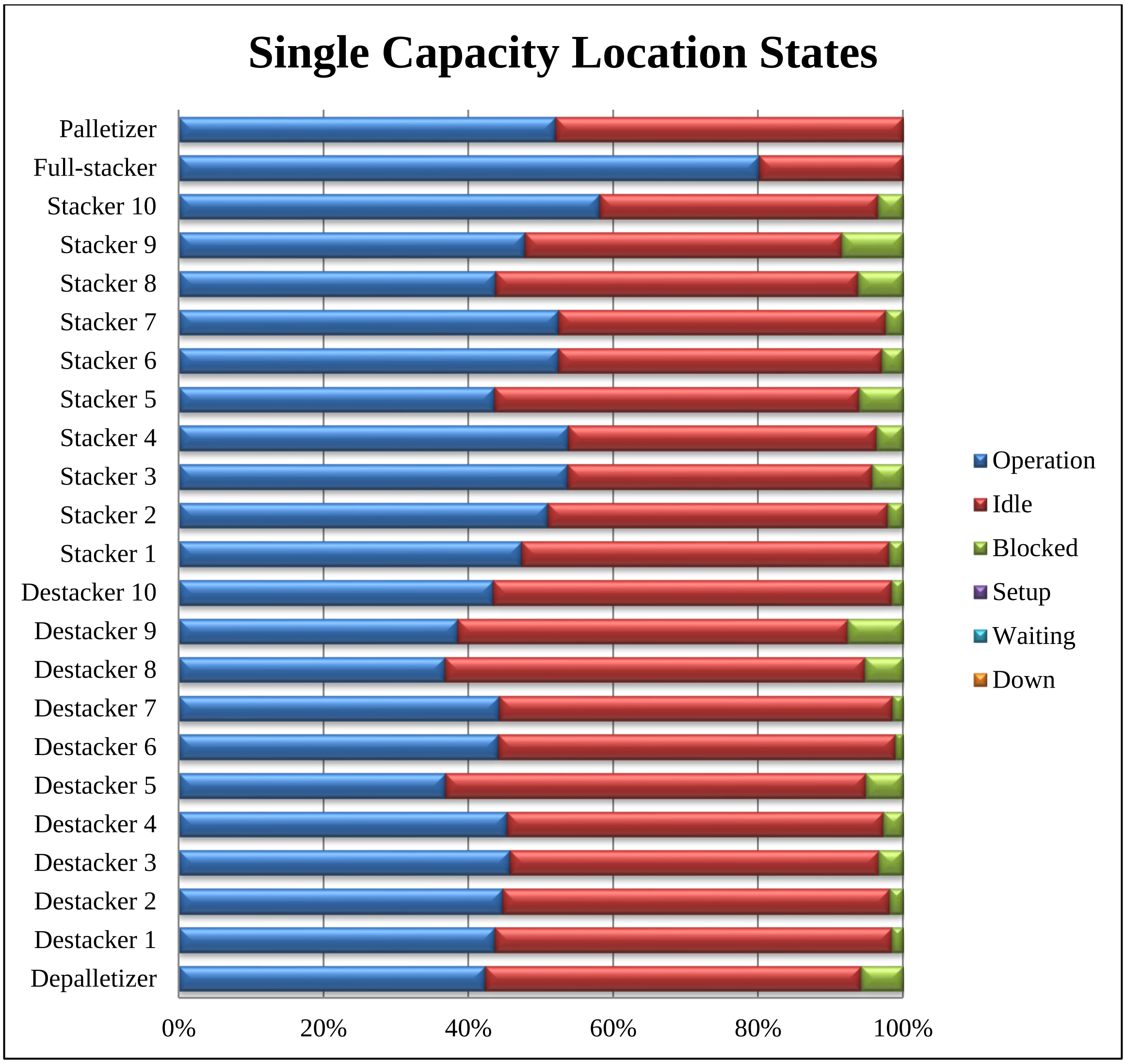


Figure 5.27 Utilization rates of all machines in the simulation scenario of 4-cycles

Normally, the blocked state of the de-palletizer is caused by the limitations of the accumulation roller conveyor before the de-stackers, where the capacity is 4 stacks. If a new replenished pallet is ordered for a line and there is at least one stack on this part of the conveyor the de-palletizing process is blocked until the capacity of this part of conveyor indicates it is empty. The blocked state of the de-stacker could be caused by a picking process from a cell located on the main conveyor before the cell that the current replenishment process is oriented towards. The blocked state of the stacker is caused by the limited capacity of the conveyor path after the stacker, where this part is designed to retrieve four stacks and no more. If this part is full, the stacker can't fee stacks to it until at least one stack place is available. Sometimes this part of the conveyor is full because the collecting conveyor is occupied by more advanced customer orders, where all stacked stacks for the next customer orders are confined until the advanced customer orders at least leave the collection area of the collecting conveyor.

5.5.2 Second scenario: three cycles to complete the OPP

In this scenario, the last two picking cycles of the first scenario are unified into a single picking cycle. The uniform load distribution in the storage lines in every cycle is illustrated in Figure 5.28, where the load in every cell is explained. The first 10 cells in Figure 5.28 represent the first storage line, and the second 10 represent the second line and so on. In the last picking cycle the total number of operated cells is 89.

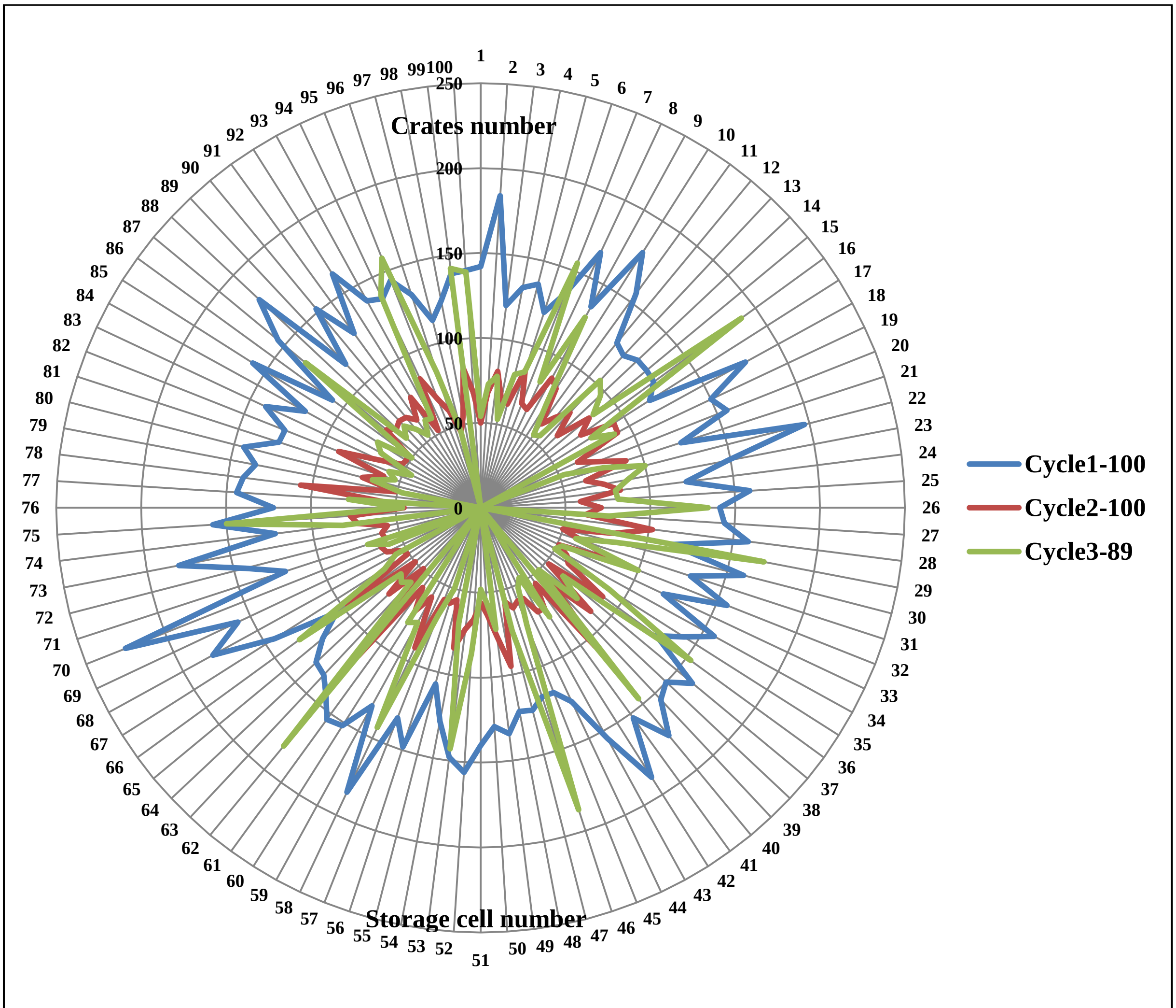


Figure 5.28 Load distributions of the articles in the storage cells in three picking cycles

This scenario is based on the combination of the other articles from every class in one simulation cycle. That means the last 18 articles from Class 12° and the last 71 articles from Class 3° were combined and simulated in one group of 89 articles. The OPP was completed in three cycles. The first cycles were for the first 100 articles from Class 12°, the second cycle was for the first 100 articles from Class 3° and the last cycle was for the other articles from every class. The results of these simulation scenarios can be summarized as in Table 5.12.

Table 5.12 Results of the simulation scenarios in case of 3-cycles

Simulation output parameters based on output pallet forms		
	13crates/stack	*6crates/stack*
Total number of products (Articles)	289	289
Total number of customers (Customers)	58	58
Total number of output pallets (Pallets-stacks per pallet)	572 (569-4, 2-3, 0-2and 1-1)	1217 (1211-4, 0-3, 4-2 and 2-1)
Total number of output crates (Crates)	28667	28667
Total number of stacks (Stacks)	2283	4854
Simulation time (Hours)	4.09	4.29
Total simulation time (Hours)	4.47	4.67
Average model's throughput (Crates/h)	6403	6129
Average de-palletizer utilization	42%	40%
Average de-stacking machine utilization	50%	48%
Average stacking machine utilization	45%	53%
Average full-stacking machine utilization	86%	75%
Average palletizer utilization	49%	98%

Unifying the last two groups of articles from every class in one picking cycle could decrease the total picking time by about 7%, but, the utilization rate of some machines could increase, such as the utilization rate of the full-stacker which increased about 6%. Based on the final output pallet form, the utilization rate of the palletizer could be increased about 50%, because the number of the output pallets increased about 50%.

Figure 5.29 illustrates the statistics of every machine in the model, where the state of the de-palletizer is summarized as about 36% of the total simulation time in the operating state, 59% in idle state and about 5% in blocked state. The average state of the de-stackers is summarized as about 46% operating, 50% idle and about 4% blocked. Similarly, for the stackers about 54% were operating, 41% were idle and about 5% were in a blocked state. The full-stacker had about 84% operating, 14% idle state and about 2% in a blocked state. For the palletizer the rate of the operating state was about 49%, about 51% was in idle state, and there was no blocked state.

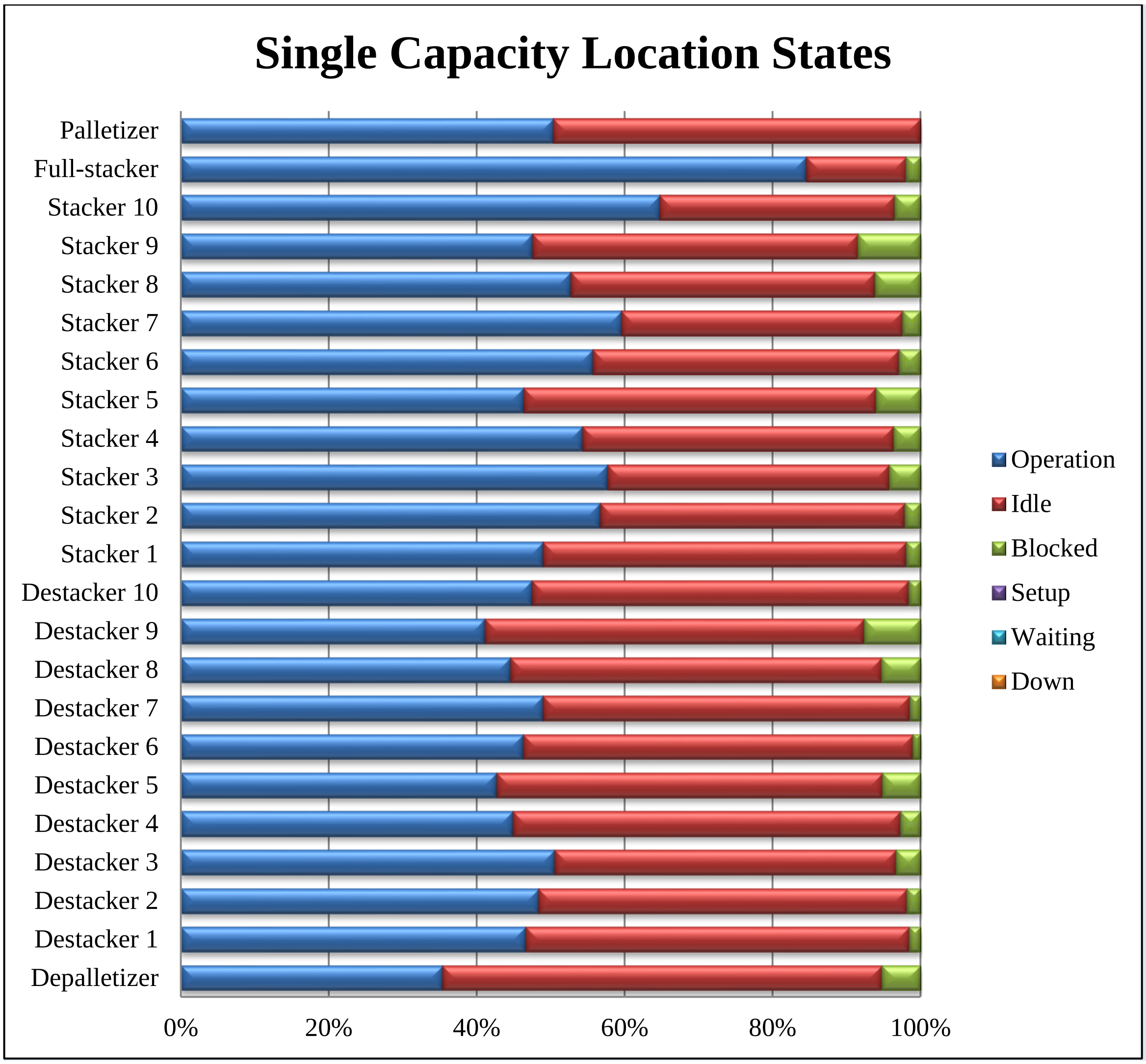


Figure 5.29 Utilization rates of all machines in the simulation scenario of 3-cycles

5.5.3 Results evaluation

It can be noted from the results that the ACCPS is capable of working with a higher number of handled articles than the number of cells in the ACCPS use-case model. Preparing the pallets before the system according to the required sequences and quantities, however, could require manual efforts and extra costs. Repackaging efforts may be required after the picking order process. The extra costs and efforts necessary were not considered, because they depend on the application area and operating conditions, which are usually different from one area to another, and therefore, this point needs more investigation, in order to evaluate the ACCPS in such application areas, where the number of handled articles is higher than the number of cells in the ACCPS. Nevertheless, ACCPS is the best system compared with other automatic full-CPS, according to the throughput, system cost, operating costs, energy consumption, and flexibility. In order to prove this, the next chapter compares ACCPS with an automatic full-CPS where the two systems have the same application area and the same constraints.

6 COMPARISON OF ACCPS WITH AN ALTERNATIVE SYSTEM

In this chapter an ACPS based on gantry robot technology (GRS) is presented, and the mathematical model is created in order to estimate the expected average cycle time. Quantitative and qualitative comparisons between ACCPS and GRS are made in order to evaluate the ACCPS. Finally the results are discussed and evaluated.

6.1 Introduction

Logistics play an increasingly important role in successful industry and business, and according to the rapid development of economic globalization and information technology, warehousing is considered an indispensable part of the logistics that play a major role. Modern warehousing systems require a quick, accurate, minimal costing and timely picking process of materials, and therefore, new fully automated OPSs are needed in order to meet these requirements. This research describes an innovative new automatic CPS for general full-case picking products. For a better evaluation of the new proposed CPS, the properties of the new system are compared with the properties of a similar, currently used, system. The system considered in this comparison process is the automatic gantry-robot-based CPS, due to the similarity in application areas, SKU handling features and logistical objectives. The main pillars of the comparison are throughput, utilization rate of the space, capacity, flexibility and cost.

6.2 Gantry Robot Case Picking System

The GRS is an automated full-CPS, which was specifically developed by the company "***CimCorp***" for production and distribution warehouses. The structure of GRS is like a bridge's structure, and moves horizontally back and forward along a set of overhead paths that cover a large area in the warehouse (see Figure 6.1).

Figure 6.1 Crated gantry robot picking system (Cimcorp, 2013)

The gantry is attached to a gripper system that can pick, lift and transport individual or multi-cases from the storage area to the output point, or from the input point to the storage area. These points are equipped with a conveyor system for transporting stacks of crates. The system is supported by a de-palletizing machine to split the incoming pallets of products into stacks, and a palletizing machine at the final output point to aggregate the picked stacks together again on a pallet. If there are several GRSs they could be integrated to one output point. It is necessary to support the system with a full-stacking machine (re-stacker) to aggregate the small picked stacks into one full-stack, or to adjust the final height of the picked stacks.

6.2.1 GRS cycle time and throughput calculation

According to Cormier and Gunn (1992), travel time models can be useful in comparing alternative operating scenarios and warehouse designs. The GRS is an order processing solution for plastic crates using robots that operate on an overhead gantry to combine buffer storage and OP functions into one flexible operation. The robots handle, store and pick crates of product in stacks. The gantry design is modular and able to accommodate any number of robots, and therefore, it can easily handle large volumes of products. Goods arrive at the input point by a conveyor in stacks of crates that contain just one SKU. A robot collects the input stacks and stores them on the floor within its working envelope, before either collecting another stack or moving into OP mode. For picking a customer’s order, the robot moves to the relevant stack for the first product in the order. If the robot has picked the required number of crates from this type of product, it moves to the next product. If the picking process is completed or the capacity of the robot is full (the robot has a full picked stack), the robot either stores it for later dispatch or sends it to a transport unit loading station, where it is moved onto a pallet or into a roll container (see Figure 6.2).

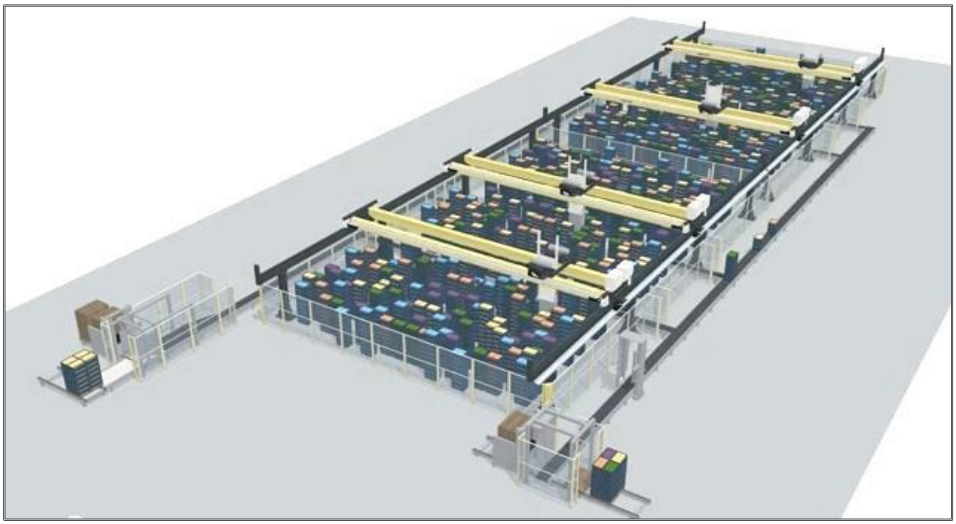


Figure 6.2 3D Layout of the GRS (Cimcorp, 2013)

Figure 6.2 shows a four units layout of the GRS use-case model for plastic boxes. This layout consists of four gantry robots. The number of robots is related to the total required throughput and the robot's throughput. The throughput of CPS is the number of crates or boxes that can be picked and retrieved within a specified period (e.g. an hour). Based on the technical information of the GRS provider, the layout of a standard GRS use-case model is described as in Figure 6.3. The width of the storage zone under the control of one gantry robot is about 10.90m. The length of this zone is about 11.90m, and therefore, the area of the storage zone will be 129.71m^2.

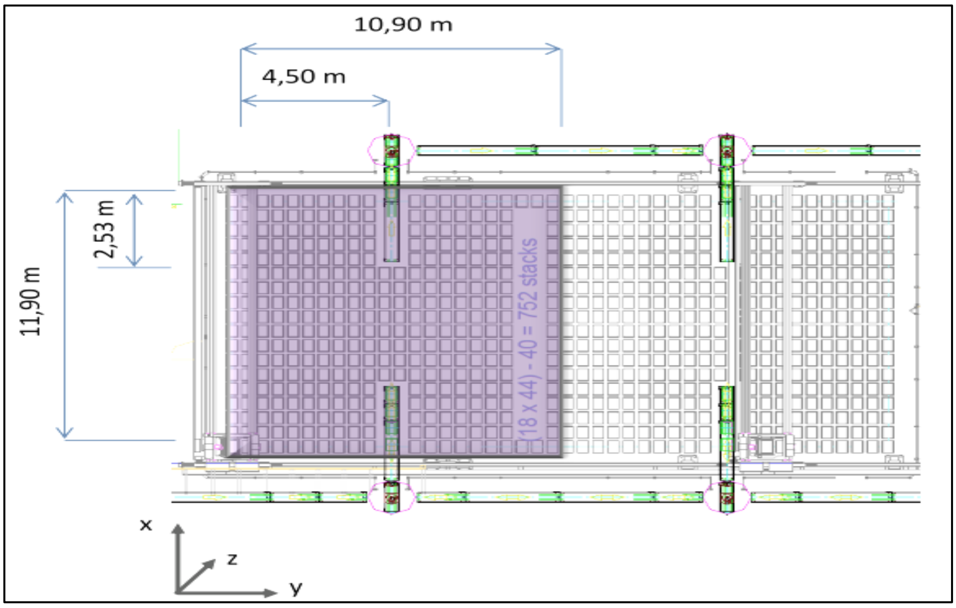


Figure 6.3 Top view of two GRS use-case model layout

The technical parameters of the GRS are determined as in the following table.

Table 6.1 The technical parameters of the GRS

Notation	Value	Definition
$\boldsymbol{v_y}$	$3.5m/s$	Maximum crane speed
$\boldsymbol{a_y}$	$2m/s^2$	Crane acceleration
$\boldsymbol{v_x}$	$4m/s$	Maximum horizontal gantry robot speed
$\boldsymbol{a_x}$	$3m/s^2$	Horizontal gantry robot acceleration
$\boldsymbol{v_z}$	$2.2m/s$	Maximum vertical gantry robot speed
$\boldsymbol{a_z}$	$4m/s^2$	Vertical gantry robot acceleration
$\boldsymbol{t_{P/D}}$	$1s$	Picking/depositing time
$\boldsymbol{t_{Pos}}$	$1s$	Positioning time
$\boldsymbol{v_F}$	$0.5m/s$	Input/output conveyor speed
$\boldsymbol{L_R}$	$2.2m$	Maximum vertical movement distance of the gantry robot
$\boldsymbol{Pick_{Max}^{Cap}}$	$13crates/cycle$	Maximum pick capacity of the gantry robot per cycle

The throughput of OPS is determined by estimating the time of one operating cycle and the number of operating cycles per hour. An operating cycle can be defined as a storage cycle, when the system picks a product from input point, travels to a storage compartment (location), releases the product there and comes back to the first point. When the start point of the operating cycle is becomes the output point of the system, this cycle can be called a retrieval cycle. Actually, the start and the end point of a storage or retrieval cycle can be a storage location that depends on the system's dwell point. To maximize the OPS throughput, two operating cycles can be sequentially performed (double cycles).

Based on the FEM 9.851 method proposed by FEM (2003) in order to determine the performance data of storage and retrieval machines and the GRS operational behavior, the expected average storage or retrieval (single cycle) cycle time (T_{SC}) of GRS use-case model is determined as

$$T_{SC} = 2 * t_{P/D} + 4 * t_z + 2 * t_{pos} + 1/2\,\{T[I/O; P1\,] + T[I/O; P2\,]\}, \qquad (6.1)$$

where

- The first term ($2 * t_{P/D}$) is the total time for picking and depositing processes in one cycle

- The second term $(4 * t_z)$ is the total time for the vertical travel time of the gantry robot in one cycle (t_z : vertical stroke time)
- The third term $(2 * t_{pos})$ is the total crane positioning time in one cycle
- The last term $(1/2\,\{T[I/O; P1\,] + T[I/O; P2\,]\})$ is the expected average maximum travel time back and forth of the crane and the gantry robot between the input/output point (I/O-point) and a point in the storage area, which represents the average travel time for the whole storage area.

To determine the value of last term, it is assumed that the behavior of the gantry robot is similar to the behavior of the automated storage and retrieval machine, where the traveling time between I/O-point and the P point, which represent the average traveling time for the whole storage area can be found by following the rules of the FEM 9.851 method proposed by FEM (2003) (see Figure 6.4).

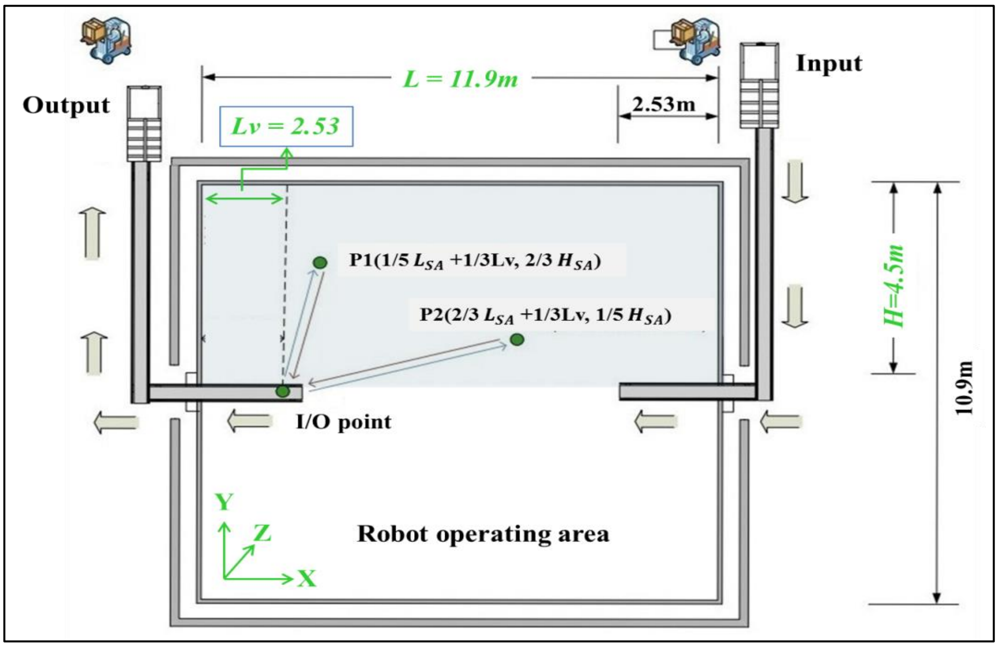


Figure 6.4 Coordination of the two points ($P1$ and $P2$) according to the FEM 9.851 method

According to the FEM (2003) and I/O position, the coordinates of $P1$ and $P2$ can be given as the following equation

$$P_1\left(\frac{1}{5}L_{SA} + \frac{1}{3}\,L_v; \frac{2}{3}\,H_{SA}\right) and\ P_1\left(\frac{2}{3}L_{SA} + \frac{1}{3}\,L_v; \frac{1}{5}\,H_{SA}\right), \tag{6.2}$$

where L_{SA} is the length of the effective storage area, L_v the shifting distance of the I/O and H_{SA} the width of the effective storage area (see Figure 6.4). The resulting coordinates of points $P1$ are (3.22m, 3m) and $P2$ are (8.77m, 0.9m). The two traveling times between the I/O-point and the two points $P1$ and $P2$ ($T[I/O;P1]$ and $T[I/O;P2]$), according to the FEM (2003), are determined as

$$T[I/O;P1] = Max\left[T^x_{I/O\rightarrow P1}; T^y_{I/O\rightarrow P1}\right], \tag{6.3}$$

and

$$T[I/O;P2] = Max\left[T^x_{I/O\rightarrow P2}; T^y_{I/O\rightarrow P2}\right]. \tag{6.4}$$

The maximum traveling time between I/O, $P1$ and $P2$ either on the x-axis or on the y-axis is the value that must be considered. In order to find the traveling time between any two points, the movement profile will determine which type of motion profile can be used to complete the move. Two common types of movement profiles are trapezoidal and triangular. A triangular move profile must be considered, if the distance between I/O and $P1$ or $P2$ on the x-axis or on the y-axis is less than or equal to the minimum distance required for the full acceleration phase to reach maximum velocity, which can be described as

$$(S^q_{i\rightarrow j} \leq a.(t_a)^2), \tag{6.5}$$

where $S^q_{i\rightarrow j}$ is the distance between the point i and the point j on q-axis, a is the acceleration of the system on q-axis and t_a is the time required by the full acceleration phase to reach the maximum system velocity on q-axis.

The trapezoidal move profile must be considered if this condition is not satisfied. That means, the distance between I/O and $P1$ or $P2$ on the x-axis or on the y-axis is more than the minimum distance required for full acceleration phase to reach the maximum velocity ($S^q_{i\rightarrow j} > a.(t_a)^2$) (see Figure 6.5).

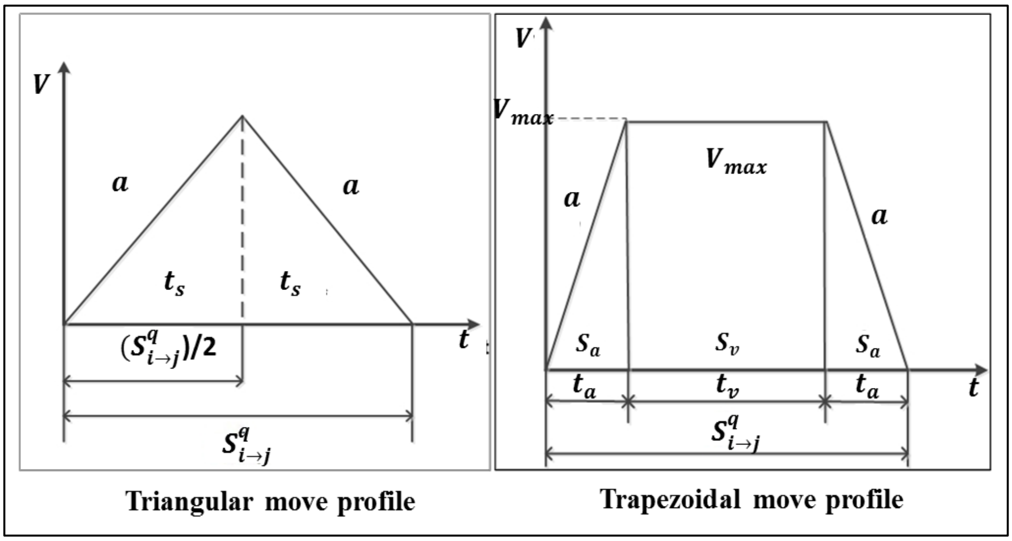


Figure 6.5 Common types of move profiles

To determine the traveling time between I/O and $P1$ on the x-axis, the distance between the I/O-point and $P1$ on the x-axis must be determined using equations (6.6) and (6.7), where X_{P_1} is the x-coordinate of the $P1$ and $X_{I/O}$ is the x-coordinate of the I/O-point as follows

$$S^{q}_{i\to j} = S^{x}_{I/O\to P_1}, \tag{6.6}$$

and

$$S^{x}_{I/O\to P_1} = (X_{P_1} - X_{I/O}). \tag{6.7}$$

After that, the minimum distance required to achieve the full acceleration phase to reach the maximum velocity (S^{full}_{a}) must be found as follows

$$S^{full}_{a} = a.(t_a)^2 = a_x * (\frac{v_x}{a_x})^2. \tag{6.8}$$

Based on the coordinates of the I/O-point, $P1$ and $P2$, as in Figure 6.6, the distance between every two points is determined, where this distance represents the first term of the constraint (6.5).

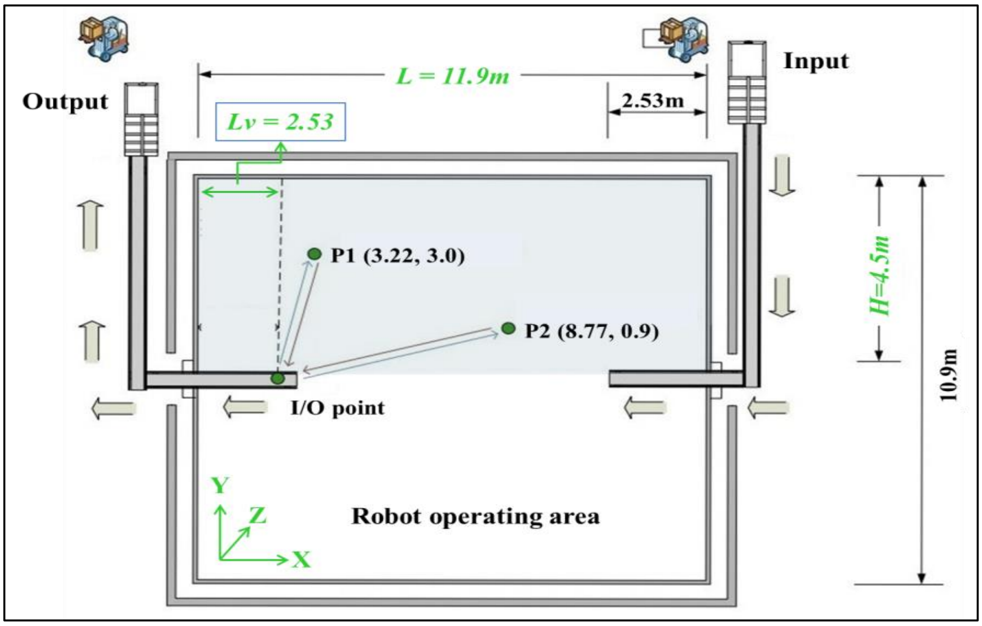


Figure 6.6 The coordinates of the I/O-point, P1 and P2

Then, if constraint (6.5) is satisfied as in the case of the traveling distance between I/O-point and $P1$ on x-axis, where the distance between (0.69m) is less than the minimum required for the full acceleration phase to reach the maximum velocity (5.33m), and therefore, the triangular move profile is the traveling form in this case (see Figure 6.5). The traveling time between the I/O and the $P1$ on the x-axis is thus calculated as

$$\frac{S^{q}_{i\to j}}{2} = \frac{1}{2}\ a.t_s^2, \tag{6.9}$$

and

$$t^{x}_{I/O\to P_1} = 2.t_s, \tag{6.10}$$

where: (6.9) is to find the time of the acceleration stage and (6.10) is to find the time of the full traveling distance (acceleration stage and deceleration stage). Based on (6.9) and (6.10), the traveling time between I/O and $P1$ on the x-axis ($t^{x}_{I/O\to P_1}$) is determined and equals 0.96s. The total traveling time between the I/O and the $P1$ on x-axis back and forth ($T^{x}_{I/O\to P_1}$) is then determined as follows

$$T^{x}_{I/O\to P_1} = 2.t^{x}_{I/O\to P_1}. \tag{6.11}$$

According to (6.11), $T^{x}_{I/O\to P_1}$ is equal to 1.92s. The total traveling time between I/O and $P1$ on y-axis ($T^{y}_{I/O\to P_1}$) is determined based on the same methodology procedures, and it is 4.89s.

In the case of the traveling time between I/O and $P2$ on the x-axis ($T^{x}_{I/O\to P_2}$), the constraint (6.5) is not satisfied, and therefore the move profile that must be considered is the trapezoidal move profile. The traveling time contains three parts of time: time due to the full acceleration phase (t_a), time due to the constant velocity phase (t_v) and time due to the full deceleration phase (t_a) see Figure 6.6.

Equation (6.8) is considered to calculate the first and the last part, and the simple velocity formula ($s = vt$) determines the middle part. $T^{x}_{I/O\to P_2}$ is thus 5.78s. In the case of the traveling time between I/O-point and $P2$ on the y-axis back and forth ($T^{y}_{I/O\to P_2}$), the trapezoidal move profile must be considered, and is 2.68s. According to (6.3) and (6.4), the maximum values must be considered, and the values of $T^{y}_{I/O\to P_1}$ and $T^{x}_{I/O\to P_2}$ were selected. By using the simple motion equation, the traveling time of the robot on the z-axis (t_z) is determined as

$$t_z = 2.t_a + t_v, \tag{6.12}$$

where t_a is the effective time of acceleration stage and t_v is the effective time of the maximum velocity stage on z-axis.

According to (6.11), the total traveling time of the robot on z-axis back and forth is 1.55s, and therefore, and according to (6.1), the total average single cycle time of GRS use-case model is 15.57 seconds, and the total number of cycles per hour (C_{nr}) is 231cycles, which is calculated as

$$\mathrm{C_{nr}} = \frac{60 * 60 * 1 \text{ hour}}{\mathrm{T_{SC}}}. \tag{6.13}$$

The maximum throughput of the GRS use-case model per hour (Thr_{Max}^{GRS}) is calculated by multiplying the total number of cycles per hour (C_{nr}) by the maximum robot pick capacity per cycle ($Pick_{Max}^{Cap}$) as follows

$$Thr_{Max}^{GRS} = C_{nr} * Pick_{Max}^{Cap}. \tag{6.13}$$

The maximum throughput of the GRS use-case model per hour is thus 3003 crates. Actually, the GRS can only reach this throughput in the case of storage or retrieval, and only when the crates are picked as full-stacks (13 crates per full-stack (per pick)). In reality, a double cycle can be achieved in one trip to increase the system throughput. The double cycle trip can start from the *I-point*, where the robot picks one full-stack, goes to $P2$, releases it there, goes to $P1$ picks new full-stack, goes to *O-point* releases it there and comes back to the *point* (see Figure 6.7).

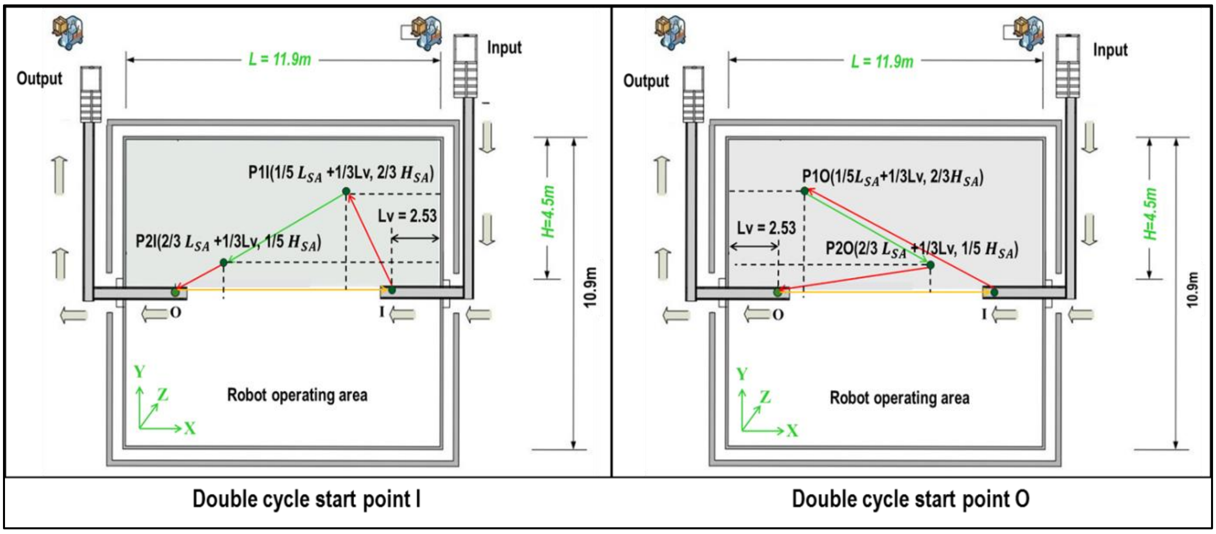


Figure 6.7 GRS double cycles layout and $P1$ and $P2$ coordinates

According to FEM (2003), the expected average double cycle time (T_{DC}) is calculated as follows

$$T_{DC} = 4 * t_{P/D} + 8 * t_z + 4 * t_{pos} + \frac{1}{2} * (\{T[I; P1\mathrm{I}] + T[P1\mathrm{I}; P2\mathrm{I}] + T[P2\mathrm{I}; O] + T[O; I]\} + \{T[O; I] + T[I; P1O] + T[P1O; P2O] + T[P2O; O] + T[O; I]\}), \tag{6.14}$$

where

$$T[I; P1I] = Max[T_{I\to P1I}^{x}; T_{I\to P1I}^{y}],$$

$$T[P1I; P2I] = Max[T_{P1I\to P2I}^{x}; T_{P1I\to P2I}^{y}],$$

$$T[P2I;O] = Max[T^{x}_{P2I\to O};T^{y}_{P2I\to O}],$$

$$T[O;I] = Max[T^{x}_{O\to I};T^{y}_{O\to I}],$$

$$T[O;I] = Max[T^{x}_{O\to I};T^{y}_{O\to I}],$$

$$T[I;P1O] = Max[T^{x}_{I\to P1o};T^{y}_{I\to P1O}],$$

$$T[P1O;P2O] = Max[T^{x}_{P1O\to P2O};T^{y}_{P1O\to P2O}],$$

and

$$T[P2O;O] = Max[T^{x}_{P2O\to O};T^{y}_{P2O\to O}] .$$

By following the same calculation methodology used in the calculation of the single cycle time, the maximum traveling times between these points (I, $P1I$, $P2I$, O and I as one cycle starting from point I and O, I, $P1O$, $P2O$, and O as another cycle starting from point O) is estimated as follows

$$T[I;P1I] = Max[0.94;2.44] = 2.44s,$$

$$T[P1I;P2I] = Max[2.71;2.05] = 2.71s,$$

$$T[P2I;O] = Max[0.89;1.34] = 1.34s,$$

$$T[O;I] = Max[3.04;0.0] = 3.04s,$$

$$T[O;I] = Max[3.04;0.0] = 3.04s,$$

$$T[I;P1O] = Max[2.87;2.44] = 2.87s,$$

$$T[P1O;P2O] = Max[2.71;2.05] = 2.71s,$$

and

$$T[P2O;O] = Max[2.89;1.34] = 2.89s .$$

The expected average double cycle time is determined as 30.92 seconds based on (6.14). The total number of cycles per hour is determined as 116.43 double cycles according to (6.12), and therefore, according to (6.13), the maximum throughput of the GRS use-case model in the double cycle operating principle is 3027 crates per hour. Nevertheless, in reality a multi-cycles picking principle would be required in order to optimize the throughput of the GRS, and therefore, throughput of the GRS based on the multi-cycle principle is calculated as follows

$$\mathrm{T_{MC}} = 2 * (1 + \mathrm{Nr_c}) * \mathrm{t_{P/D}} + 2 * (3) * \mathrm{t_z} + 2 * \sum_{\mathrm{i}\to 1}^{\mathrm{Nr_c}} \mathrm{t_z} - ((\mathrm{i} - 1) * \tfrac{\mathrm{t_z}}{\mathrm{Nr_c}})) + (3 + \mathrm{Nr_c}) * \mathrm{t_{pos}} + (2 + \mathrm{Nr_c}) * \mathrm{T[P_i;P_{i+1}]} + \mathrm{T[O;I]}, \quad (6.15)$$

where

- $\mathrm{T_{MC}}$: The expected average multi-cycles time,
- Nr_c: Number of cycles or points that must be visited to pick the full capacity of the GRS robot based on the average number of the ordered crates per order-line,
- $2(1 + Nr_c) * t_{P/D}$: This term represents the pick and deposit time for all points located on the path of the robot trip. The digit 1 is added to the Nr_c because there is an additional point that must be considered (the storage point due to the storage process of the full stack).
- $2 * (3) * t_z$: This term represents the full traveling time in the z-direction for the three additional points,
- $2 * \sum_{i \to 1}^{Nr_c} t_z - ((i-1) * \frac{t_z}{Nr_c}))$: This term represents the traveling time in the z-direction for the visited points. The average number of ordered crates per order-line and the height of the stack were considered here,
- $(3 + Nr_c) * t_{pos}$: This term represents the positioning time for all points,
- $(2 + Nr_c) * T[P_i; P_{i+1}]$: This term represents the total traveling time between all points except the traveling time between output point and input point, which is calculated according to the last term,
- $T[P_i; P_{i+1}]$: The expected average traveling time between every two visited points or locations, where

$$T[P_i; P_{i+1}] = Max\left[T^x_{P_i \to P_{i+1}}; T^y_{P_i \to P_{i+1}}\right]$$

  and $T^x_{P_i \to P_{i+1}}$ is the traveling time between the two points on x-axis. Based on the logic of the average distance between points on x-axis, the average distance between every two points on the x-axis is determined as the length of the working area plus the minimum traveling distance between two points on the x-axis divided by 2, and then by dividing this distance by x-velocity, the $T^x_{P_i \to P_{i+1}}$ is determined. The same principle for $T^y_{P_i \to P_{i+1}}$, the width (height) of working area plus the minimum traveling distance between two points on the y-axis is divided by 2 and by y-velocity to determine $\mathrm{T}^y_{\mathrm{P_i \to P_{i+1}}}$, and
- $\mathrm{T[O; I]}$: Traveling time of the GRS between the input point and the output point.

Therefore, if the Nr_c is 5, the $\mathrm{T_{MC}}$ according to (6.15) is 60.9 seconds. There are 59.1 operational cycles per hour are with maximum expected throughput of about 1536.94 crates per hour. This means that the number of positions that must be accessible to supplement the capacity of the robot is increased whenever the final throughput of the system is decreased.

6.2.2 GRS evaluation based on the parameters of the case studies

According to the parameters of the two case studies discussed in Sections 5.4 and 5.5, the performance of the ACCPS can be evaluated in comparison to the GRS performance under the same operating parameters.

First case study: the total number of required crates is about 44,640 crates per day, and the average number of ordered crates per order-line is 2.67. According to (6.13), the expected average throughput of the GRS for single cycle operating principle is thus 616.77 crates per hour, and for the double cycle operating principle, the expected average throughput of the GRS is 621.74 crates per hour. According to the multi-cycle operational principle, however, where Nr_c equals 4.87 (approximately 5), the expected average throughput of the GRS is 768.47 crates per hour, and therefore, at least 58.09 operating hours are required for one GRS use-case model to pick the total required crates per day based on the double cycle operating principle. That means that several GRS use-case models must be installed to finish the OPP in 8 hours. By installing 8 GRS use-case models, the OPP time for the whole quantity can be decreased to 7.26 hours; however, one ACCPS use-case model can execute the OPP of the entire required quantity in only 7.26 operating hours.

Certainly, the initial cost of every system is different; the expected initial cost of one GRS use-case model is about 1 million Euros, and the expected cost of a solution based on the gantry robot technology is estimated to reach 8 million Euros. Nevertheless, the solution cost of the same case study based on ACCPS technology is estimated to reach only 3 million Euros. During the storage and retrieval processes the energy consumption of the GRS is more than that of the ACCPS due to the heavy movable crane mass (high dead load /payload ratio). Dead load is the moving mass of the system structure, it is not desirable in movement systems, but it is not possible to avoid it. The payload is the total desired load that must be moved, and it is equal to the material load that must be transported or handled, such as pallets, crates, boxes and any other form of transported material. The proportion of the dead load to the payload can directly indicate system efficiency, especially according to energy consumption. If the dead load decreases, the energy efficiency of the system increases, and therefore, the energy efficiency of the ACCPS is better than GRS. According to Furmans (2011), about 65% of the energy consumption of the GRS use-case model goes to the dead load (crane mass), while the ACCPS dead load is so small that it can be omitted in the calculations.

Second case study: the total number of required crates per day is about 28,667, and the average number of ordered crates per order-line is 2.7. According to (6.13), the total average throughput of the GRS for single cycle is thus 623.7 crates per hour, and for the double cycle operating principle, the total average throughput of the GRS is determined as 628.7 crates per hour, but, according to multi-cycle operational principle, where Nr_c equals 4.81 (approximately 5), the expected average throughput of the GRS is 768.47 crates per hour, and therefore, for one GRS use-case model at least 37.3 operating hours are required to pick the total required crates per day. As a result, several GRS use-case models must be installed to finish the OPP in the available time. By installing 7 GRS use-case models, the OPP time for the whole quantity can be decreased to 5.33 hours; however, only 5.057 operating hours are required for one use-case model based on ACCPS technology being used to execute the OPP of the whole required quantity per day.

6.3 Quantitative and Qualitative Comparison of ACCPS with GRS

To evaluate the performance of any OPS, many aspects must be discussed and analyzed. According to the evaluations of these aspects, the best OPS and technology can be selected and applied to obtain the most expected benefits. These aspects can be divided into four groups: logistics aspects, economical aspects, structural aspects, and operational aspects. These aspects will be discussed in the following sections. This section presents a numerical comparison between the ACCPS and the GRS based on the parameters of the two case studies, and an analytical comparison between the two systems based on the analysis of their operating principles and structures.

6.3.1 Logistics aspects

The most important logistical aspects discussed are *the system's throughput, storage capacity, storage density, required area and height, and average order cycle time*. Actually, storage density depends directly on the building height, and therefore, the storage density decreases when the warehouse height increases, but it should be taken into account that this increase is more than what is required to build the OPS. To evaluate the performance of the two systems (ACCPS and GRS) according to the comparative logistic aspects, all parameters of these two systems regarding their performance, and based on the parameters of the two case studies were analyzed and are summarized in Table 6.2.

Table 6.2 The logistical comparison results of the ACCPS vs. GRS

ACCPS compared with GRS according to the case studies' parameters				
	ACCPS		**GRS**	
	Case study1	*Case study2*	*Case study1*	*Case study2*
Total number of products (Articles)	**100**	**289**	**100**	**289**
Total number of customers (Customers)	**675**	**58**	**675**	**58**
Total number of output crates (Crates)	**44640**	**28667**	**44640**	**28667**
Average order size/order-line (Crates/order-line)	**2.67**	**2.7**	**2.67**	**2.7**
Min. expected cycle time (Seconds)	**2.4**	**2.4**	**15.57* 30.92** 60.9*****	**15.57* 30.92** 60.9*****
Max. use-case model throughput storage and retrieval (Crates/h)	**15000**	**15000**	**3003* 3027** 1599*****	**3003* 3027** 1599*****
Max. use-case model retrieval throughput based on average order size/order-line (Crates/h)	**6059**	**5669**	**616.77* 621.74** 768.47*****	**623.7* 628.7** 768.47*****
Use-case model required height (m)	**13.75**	**13.75**	**5**	**5**
Use-case model storage required area (m^2)	**80.5**	**80.5**	**129.71**	**129.71**
Use-case model capacity (Articles/model)	**100**	**100**	**376**	**376**
Use-case model capacity (Crates/model)	**5200**	**5200**	**4888**	**4888**
Storage density per use-case model for storage area (%)	**19.7**	**19.7**	**31.6**	**31.6**
Total OP time per use-case model based on average order size/order-line (Hours)	**6.98**	**5.057**	**71.8** 58.09*****	**45.6** 37.3*****
Expected required number of the use-case models (Models)	**1**	**1**	**10** 8*****	**8** 7*****
Total expected OP time (Hours)	**6.98**	**5.057**	**7.18** 7.26*****	**5.7** 5.33*****

*Single cycle operating principle (S or R), ** Double cycle operating principle (S and R), and *** Multi-cycle operating principle (to fill the robot capacity based on the average order size/order-line).

The most significant result of this comparison is that the productivity of one ACCPS use-case model is about 10 times higher than the productivity of one GRS use-case model.

6.3.2 Economic aspects

The most important points that should be here considered are: *system's initial cost, operating cost, maintenance cost, energy cost and investment cost payback time (ROI)*. The expected operating cost here refers only to maintenance and energy costs, without any additional costs such as operator costs, pallet preparation costs before the OPS, transport costs of pallets from the OPS to the shipping area, etc. The comparison between the two systems is summarized in Table 6.3. The initial cost of every solution is different; the initial cost of the solution based on the GRS technology for the second case study is about 8 million Euros, while the initial cost of the ACCPS-based solution is not more than 3 million Euros. ACCPS is better than GRS as regards energy consumption, because of the heavy dead load of the crane in the GRS, while there is a negligible dead load in the ACCPS.

Table 6.3 The economic comparison of the ACCPS vs. GRS based on first case study parameters

ACCPS compared with GRS based on the parameters of the case studies		
	ACCPS	**GRS**
Initial cost of the use-case model (Euros)	**2,822,528**	**1,000,000**
Operating cost (Euros/year)	**129,391**	**129,391**
Number of the required use-case models (Models)	**1**	**8**
Total initial cost (Euros)	**2.8 million**	**8 million**
Annual Operating saving costs (Euros)	**993,808**	**993,808**
ROI (%)	**35.2**	**12.4**
Payback period (Years)	**2.84**	**8**

Although the initial cost of one ACCPS use-case model is about 3 times higher than the initial cost of one GRS, this depends on the application area, and the total solution cost based on the ACCPS technology can be lower than the total solution cost based on GRS technology about 3 times.

6.3.3 Structural design aspects

The system structural components, flexibility for growth, and the flexibility of the system structure according to the warehouse building and handled SKUs are the most important points considered in the structural comparison. The flexibility of the ACCPS structure gives the system very high potential for adaptation to building constraints. The ACCPS structure also consists of individual modules (cells, conveyors, etc.), which gives it more capacity for adapting, and therefore, adding a new storage line to an existing use-case model, or number of cells to an existing storage line will not cause great problems. The heights of the cells can be adjusted according to the practical condition (e.g. the roof form). The cells can be designed with many different heights to increase the roof space utilization rate as in Figure 6.8.

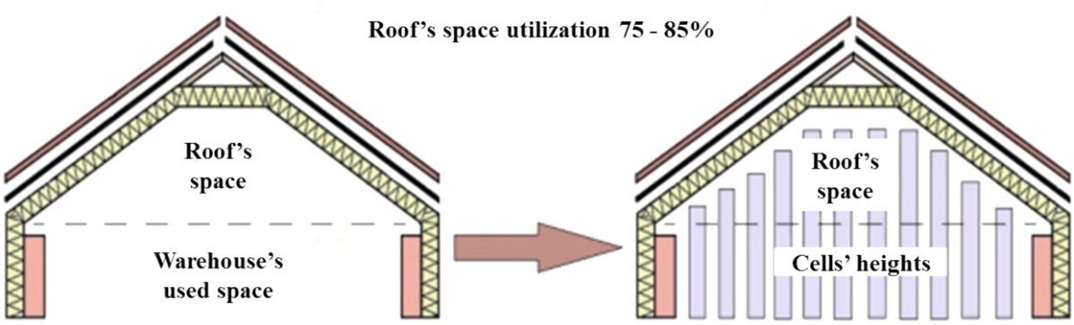


Figure 6.8 Flexibility of ACCPS structure and roof utilization rate

From the horizontal perspective, the ACCPS is also adjustable, the extension of the ACCPS storage line is determined according to the number of installed cells in it (see Figure 6.9).

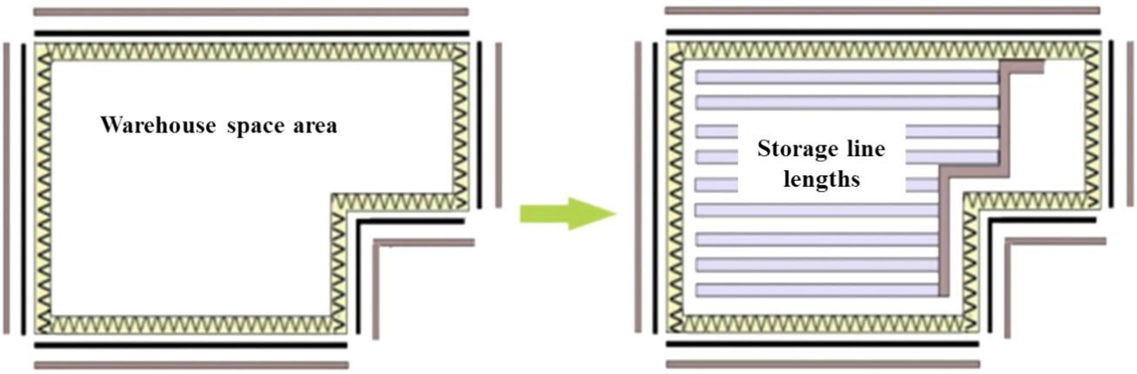


Figure 6.9 Flexibility of ACCPS structure and utilization rate of the warehouse's area

According to the flexibility of the ACCPS structure, the cells can be rearranged to adapt the ACCPS general layout with the construction or operation constraints. The same number of cells can be rearranged into more lines to increase the throughput, or the cells can be rearranged into fewer lines to decrease the initial system cost by decreasing the number of de-stacking and stacking machines. During troubleshooting only the defective part(s) can be shut down and the others parts can be operated without any problem.

The maintenance hallways would be unnecessary if the storage lines were redesigned to be movable lines, which could increase storage density. The compact ACCPS use-case model design has only one floor area for maintenance purposes (see Figure 6.10).

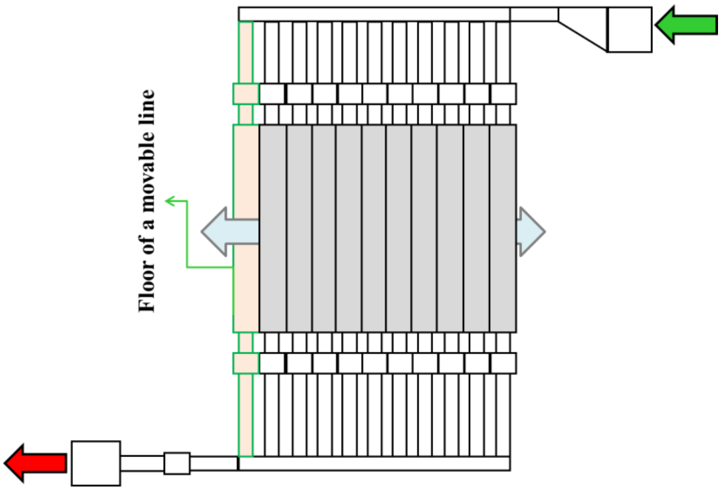


Figure 6.10 Compact ACCPS use-case model

By eliminating the maintenance area from the storage area, the storage density increases to 25%, however, it must be considered that there will be additional costs to the system, such as the cost of the system that moves the storage lines and the additional cost of the new structures and parts of the movable storage lines.

6.3.4 Operational aspects

Operation mainly consists of the following aspects: *operating principles of the system, application areas, and system accessibility to SKUs*. Due to the ACCPS structure, a very high operating flexibility can be reached, many operating strategies can be applied, and moving from one strategy to another can be accomplished easily and very smoothly. Many operating scenarios can be applied, such as storage and retrieval at the same time, single storage process, single retrieval process, and storage in some lines and retrieval from others at the same time. ACCPS can execute OPP for either one customer or for several at the same time. The ACCPS can be applied in a wide range of areas that require high daily throughput, hard and dangerous operating areas, and in areas where a very short delivery time is required. Many energy saving ideas can be applied. If the OPP of a required article is in progress from a cell and at the same time the replenishment process is executed to the same cell, a great deal of energy can be saved by transporting the required crates directly to the output points. By using this principle, both energy and time can be saved. Time and energy consumption can be varied from one operating scenario to another, depending on the time, point and period of the replenishment process and picking process events for the same article when they occur at the same time.

6.4 Summary

The ACCPS has many ‘pros’ in comparison to other automatic full-case picking solutions, but, at the same time it has some ‘cons’, such as the system limitation related to the physical shape constraints of the handled crates. This is a general problem, however, found not only in ACCPS, but in all automatic full-case picking solutions. The profit from the system depends on the parameters of the application area, such as number of articles, order volumes and the like. The operating constraints, investment constraints, application area constraints and others have a significant effect on user decisions in order to select the best OPS. There are general elements that support any OPS, however, and can be compared with another, such as throughput, initial cost, ROI, and payback period. These points are the most important selection parameters of the best OPS, and ACCPS would be the best system compared with the other existing systems based on these parameters.

As previously identified, ACCPS is designed to handle a low variety of products (not more than hundreds) with a high pick rate (several thousand of cases per hour). This operational environment would be the best application area for the ACCPS, but, the main idea of the ACCPS, as based on the cells as a dispenser buffer system for cases, could also be suited to slow moving product lines within a DC. The operational environment of slow moving products requires an OPS that handles a high variety of products with low pick rates, and therefore, the ACCPS use-case model could be designed to handle the slow moving products, where several articles could be stored in every cell. The total number of articles that could be stored in one cell is determined by dividing the capacity of the cell by the average number of stored crates per article within the cell. That means that if the cell capacity equals 60 crates and the average number of stored crates per article equals 6, then the total stored articles within the cell would be 10 articles. If the number of the cells in one ACCPS use-case model equals 100, then the total number of the handled articles would be 1000.

Based on the LIFO principle of crate flow within the cell, it is possible to access only one article per cell directly. The accessibility of a certain article stored in the cell depends on its entering time among other articles entered in the same cell. That means that the most recently stored article has the highest accessibility, the lowest accessibility is for the first stored article within this cell, and therefore, the accessibility of the article and the average accessibility of any article within the cell are determined as follows

$$Acc^{Art^i} = 1 - \frac{(i-1)}{i}, \tag{6.16}$$

$$Acc^{ave} = \frac{\sum_{i=1}^{k} 1 - \frac{(i-1)}{i}}{k}, \tag{6.17}$$

where Acc^{Art} is the accessibility of the article, Acc^{ave} is the average accessibility of any stored article within the cell, k total number of stored articles within the cell, and i represents the article's storage position in the cell, where the lowest article's storage position within the cell takes the value of $i = 1$ and the highest article's storage position within the cell takes the value of $i = k$.

Based on the ACCPS use-case model discussed in Section 4.6.2, the expected minimum and average retrieval time of first crate of the required article from the multi-article cell are determined as follows

$$min.R.T_{first\ box}^{req.art^i} = 2.4 + 2.4 * (1 - \frac{(i-1)}{i}) * Nr._{crates/art}^{ave}, \tag{6.18}$$

$$Ave.R.T_{first\ box}^{req.art} = 2.4 + 2.4 * \left[\frac{\sum_{i=1}^{k} 1 - \frac{(i-1)}{i}}{k}\right] * Nr._{crates/art}^{ave}, \tag{6.19}$$

where $min.R.T_{first\ box}^{req.art}$ is the excepted minimum retrieval time of the first crate of the required article stored in a multi-article cell, $Ave.R.T_{first\ box}^{req.art}$ is the excepted average retrieval time of first crate of the required article stored in a multi-article cell, and $Nr._{crates/art}^{ave}$ is the average number of stored crates per article.

If the required article is not in the first article storage position within the multi-article cell (lowest article in the cell), the articles that blocked the way of the required article must be retrieved from this cell in order to pick the required article. The unwanted crates of the unwanted articles could be restored in other cells on the same line or could be restored in the same cell after retrieving the wanted crates from the wanted article. The replenished crates of any article could be directly sent to the correct cell at the correct time to be in the correct position based on the OPPs sequences. Actually, this operating principle must be further analyzed and investigated in order to evaluate the ACCPS performance under all operating strategies. Several design aspects must be re-discussed and reevaluated in order to optimize the ACCPS layout according to the new operational environments and the new required throughput. A very high-complexity control system would be required in order to control and manage all OP strategies. Applying the ACCPS in the slow moving products area is a suggested subject for future research.

7 CONCLUSIONS AND FUTURE RESEARCH

In this chapter, the most important conclusions of the research are summarized. The contributions, the limitations and suggestions for future research are presented.

7.1 Conclusions and Contributions

The first conclusion of this research involves the investigation of the most suitable mechanical design, operating principle and controlling principle with respect to productivity. The ACCPS is efficient and flexible, and, thus it meets market requirements for several industries which produce high quantity and low variety products. The structure of the ACCPS explored in this research has the potential to create a new generation of ASRSs. It could also be considered the entrance to a deeper understanding of the possibilities of building a new modern storage system as a full and comprehensively controlled system. Features include a window to reorganize the relationship between the warehouse and the customer by redesigning the OPP. By using an intelligent control, communication and information technology system, the customer can accomplish OPP directly from the ACCPS in the warehouse without any intervention from the warehouse employees.

The conclusion of the research regarding economic issues was based on changing the use of standard mechanical systems to the new concept by altering the tasks of these systems. For example, the use of a mechanical lifting system for cases is changed to that of a buffering system or storage rack. Standard components are thus used to decrease fixed costs. To decrease operating costs in the new system, all processes were automated to avoid dependence on workers as far as possible. To further reduce the operational costs (especially, the energy costs); the system was designed to include no dead payload. It has only an active payload (SKUs) which means that all the energy is spent in transporting the SKUs within the system. The system has no mechanical transaction structures such as stacker cranes or shuttles.

Buildings on the results of the real-time data test in Chapter 5, numerous suggestions for improvement are discussed, aiming to optimize the OPP. This is a real practical case designing genuine OPS, and considered the complexity of the OPS design problem. This research presents a comprehensive solution for reducing the cycle time. In addition to the evaluation of the new system proposed in this research, many improvement ideas were suggested and discussed in order to optimize the new design, and many new aspects related to levels of flexibility were explained.

The theoretical contributions of this research can be summarized in the overall aim of the research to develop a new, very high-throughput, automatic CPS that will support knowledge and enhances the literature about the successful use of automation in internal logistics systems. In-depth investigations of automatic CPSs are scarce in the literature, and therefore, this research contributes to bridging the research gap.

The practical contribution of this research can be summarized in the overall research methodology to solve the OP design problem. Designing an OPS is a complicated process that requires a clarified methodology and framework. Yoon and Sharp (1996), and Dallari et al. (2009) proposed an OPS design methodology for which the system proposed in the current research can serve as a practical application. This research clarified the role and the benefits of the automation in the internal logistics systems, especially for OPP, and opened the door for more automation levels in warehouses, DCs and other application areas.

7.2 Limitations

While the simulation model is considered sufficient to support the proposed system, empirical analysis using a practical prototype can add further support that might be lacking in the current research. Empirical evaluation can support the validity of the results and enhance the robustness of the system's mechanical structure. The focus of this research was on the OPS design, and therefore the ACCPS use-case model was designed and analyzed separately, without considering the possible effects of other parts of the warehouse system. In other words, the effect of all activities taking place before the case picking area (in reserve area), and after that (in consolidation area or in shipping area), were not considered, however, no negative external effects were imposed in the OP area. The data limitations of the real case studies prevented the consideration of external effects on the new design.

7.3 Future Research

In this research, a simple analytical model was used to calculate the throughput and the OP time of the system, and a simulation model was used to solve the storage location assignment problem and to determine the best the OP strategy. Several optimizing scenarios were analyzed and discussed in order to optimize the throughput of the ACCPS, and therefore, a comprehensive mathematical model that determines the optimal throughput of the system based on solving the storage location assignment problem considering with the optimal OP strategy could be significant complementary research in the future. The results of the comprehensive mathematical model could be supported by the results of a simulation model or with empirical results.

Based on the main idea of the ACCPS' design, and especially the cell structure and operating principle, many ideas and suggestions could be introduced in order to adapt the ACCPS for use in many application areas where the ACCPS's basic structure was originally not compatible. The limited capacity of the ACCPS and the low number of articles that the system is able to handle in one picking period are the main reasons for the limited applicability of the ACCPS. Future research could involve redesigning the ACCPS structure in order to increase the system capacity and the number of handled articles per picking period. The suggested design could be based on the cell structure as a feeder to many flow rack levels on one side and as extractor on the other side. Such a design could handle up to 1000 articles and the system capacity could be around 52000 crates, if there were 20 columns of crate flow racks installed back to back, every column has 50 levels one over another, where 20 cells as feeders are installed on the input side, 20 cells as extractors on the output side, and the capacity of every flow rack was 52 crates or more. All technical parameters and features of the new design must be determined, discussed and analyzed. More investigations are required in order to optimize the article distribution algorithm for the cells and the OP strategies (customer lists or priorities). Suggested future research related to this point could involve the creation of a mathematical model and an algorithm to determine the best article location within the ACCPS and the optimal customer list for the optimal OP time and throughput.

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