# Automated or Manual Storage Systems:

# Do Throughput and Storage Capacity Matter?

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***Abstract***

Selecting the appropriate type of capital-intensive storage systems is an important decision for warehouse managers. However, such a decision is complex due to various available storage systems. In addition, warehouse requirements such as storage capacity and throughput influence this decision. This research provides insights that enable managers to select the suitable type of storage system which minimizes the investment and operational costs while the warehouse design requirements, in particular the storage capacity and throughput, are met. To obtain these insights, an Excel®-based decision support system is developed for a set of most common types of manual and crane-based automated storage systems in pallet and case warehouses. The decision support system uses the closed-form formulas from the warehousing literature and also Monte Carlo simulation to approximate the travel time in each storage system. The results show that the choice of automated or manual storage system and the associated costs depend on the required capacity and throughput. When the storage capacity and throughput are low, the manual pallet racks are the preferred storage system and incur the lowest costs. As the storage capacity and throughput increase, there is a need for more compact storage systems that can store more loads in a smaller footprint. Thus, for medium to high capacity levels, double-deep automated storage systems and deep-lane compact storage systems are the ones with the lowest investment and operational costs. The results for the case warehouses show that the investment and operational costs increase rapidly with an increase of the throughput. In particular, the increase is noticeable for operational costs of shelf rack system and the investment cost of miniload system where the storage capacity and throughput level are high.

*Keywords*: Facility layout; cost analysis; layout design; storage system selection; decision support system

## *1. Introduction*

Warehouses can be distinguished based on their physical, operational and flow characteristics. Physical characteristics of warehouses are for instance the warehouse layout, the number of dock doors, and the type of storage system. The physical characteristics have to be decided at the design phase. Modifying the physical layout of a warehouse or selecting the type of storage system is an expensive project and requires a large investment. Operational decisions on the other hand are less costly and can be decided in a later stage. Examples are the truck loading scheduling, arrival and departure patterns and product interchangeability (Van Belle, et al., 2012).

Several types of manual and crane-based automated storage systems can be used in warehouses and the selection of the appropriate type of system is very important, as it affects the overall warehouse cost and performance. Kulak (2005) argues that selecting the appropriate warehousing storage system can reduce investment and operational costs, decrease lead times, improve facility utilization, and increase productivity. The storage system selection is a strategic decision which addresses the level of automation in a warehouse. Determining the type of storage system and best level of automation is not a simple task and in practice the decision is often based on experience of designers and managers. Gu, et al. (2010) discuss that the academic research on storage system selection is scarce; so, there is a large gap between the academic literature and the practice of warehouse design. To bridge this gap, this paper aims to estimate the investment and operational costs of manual and automated case and pallet storage systems considering two main design inputs: required storage capacity and throughput. The required storage capacity and throughput are considered as the two main inputs in designing and selecting a warehouse storage system (see e.g. Bartholdi and Hackman, 2017; Frazelle, 2002). To our knowledge, this paper appears to be the first in the literature which addresses such an important design decision in warehousing and provides relevant guidelines and insights to distribution managers. Since the focus of this paper is only on the comparison of storage systems, other warehouse activities which do not require storage and retrieval (such as cross-docking) are not considered in this paper.

In order to perform this research, a Microsoft Excel®-based decision support system (DSS) is developed. The warehouse design DSS gives insights in the investment and operational costs of each type of storage system based on the expert inputs. For each storage system, the DSS uses the closed-form travel time models developed in the warehousing literature to calculate system throughput for a given storage capacity and configuration (e.g., Hausman, et al. (1976) develop travel time models for single-deep automated storage and retrieval systems, AS/RS). For systems where no closed-form travel time expressions exist in the literature, Monte-Carlo simulation is used (e.g. mobile racking storage system, see Section 3.2 for details of DSS). Then, the investment and operational costs for the storage systems under study is calculated using the Microsoft Excel® DSS (the cost components and calculations are described in Appendix I). To make a fair comparison, the storage systems with the same storage capacity and throughput, the same unit of handling (pallet or case), and under the same storage policy (random storage) are compared. As the system configuration (e.g. length and height of a rack in an AS/RS) influences the system throughput, the system optimizes the system configuration within a practical range resulting in minimum investment and operational costs. In our DSS, the most common types of storage systems ranging from manual systems such as shelf and pallet racks to crane-based automated systems such as deep-lane compact storage systems and double deep AS/RSs are considered. In total nine types of storage systems are evaluated in the DSS (see Appendix II for an overview of considered storage systems). In addition, the input parameters (storage location dimensions, crane speeds, cost components, etc.) and the resulting outputs are validated in order to obtain more realistic outcomes. Beside the theoretical and practical contributions of this paper, the DSS developed in this paper is Microsoft Excel®-based and can be easily deployed by warehouse managers and consultants to draw practical insights. In fact, the system has already been used to give consultation to European logistics providers and material handling suppliers.

This paper is organized as follows. Section 2 reviews the warehouse storage systems and the previous research on warehouse storage system selection. Section 3 proposes a conceptual model and the research methodology for this research. Section 4 discusses the analysis and results and validates the DSS. Finally, section 5 concludes the paper and discusses managerial implications and avenues for future research.

## *2. Literature Review*

The storage system selection problem deals with the automation level of the warehouse and the appropriate type of storage system. Such decisions are capital-intensive and should be made at the strategic level, next to other strategic decisions such as the well-studied warehouse location problem (Khumawala and Kelly, 1974) or the network design problem (Lee, 1996; Ben-Ayed, et al. 2014). Selecting the appropriate type of storage system is far from straightforward and has been rarely studied in the warehousing literature (see, for example, the literature reviews by De Koster, et al., 2007 and Roodbergen and Vis, 2009). Among the handful of studies, White, et al. (1981) are the pioneers to use analytical models to compare different automated and manual storage systems with the objective to determine the minimum space design. In a later effort, Matson and White (1981) develop a total cost model which evaluates the space and material handling costs. They analyze the effect of handling requirements on the optimum storage design. Based on a cost-productivity analysis technique, Cox (1986) develops productivity ratios to evaluate different levels of automation. Sharp, et al. (1994) compare shelving systems, modular drawers, gravity flow racks, carousel systems, and miniload storage/retrieval systems. For different product sizes and dimensions, they evaluate the total cost including the floor space costs, operational costs, and equipment costs. Hassini (2009) review, summarize and categorize the major studies on the one-dimensional storage location problem in carousels. They also present a model to find optimal storage locations for items with the objective of minimizing the average retrieval time in a single carousel system. In sum, research on storage system selection is scarce as also confirmed in the recent literature review by Gu, et al. (2010).

In spite of its importance, few papers have studied the warehouse design problem (Baker & Canessa, 2009). Most research within the warehousing literature seems to focus on fine-tuning the warehouse organization on tactical and operational levels. These studies mainly focus on a simplified representation of a warehouse problem, often well-defined and directed towards a particular aspect (e.g. arrangement of layout, operational policies, etc.). Selecting a storage system requires two main steps: first, the storage system alternatives that are appropriate for storage/retrieval requirements have to be identified. Second, the storage system with the minimum total costs which satisfies the storage capacity and throughput requirements has to be selected. In fact, selecting a warehouse storage system is one of the decisions in the larger process of warehouse design, a series of decisions related to the physical and operational characteristics of a warehouse. The general approach to make such decisions varies in the literature. According to Gu, et al. (2010) warehouse design involves 5 major decisions: (1) determining the overall warehouse structure, (2) sizing and dimensioning of the warehouse and its departments, (3) determining the detailed layout within each department, (4) selecting warehouse storage system and equipment, and (5) selecting operational strategies. Rouwenhorst, et al. (2000) identify that the decisions regarding the design of a warehouse system are interrelated and define warehouse design as a structured approach of decision making at strategic, tactical and operational levels. The selection of the warehouse storage system type at the strategic level requires a high investment. Ashayeri and Gelder (1985) argue that warehouse designers face three main issues. These issues are to select the best storage method, to choose the right storage and material handling equipment to facilitate this method and finally to determine the warehouse layout. Park and Webster (1989) investigate the implementation of a three-dimensional storage system and find that determining and selecting an optimal storage system for storing and retrieving products is a very complex problem due to the inter-relationship between the overall warehouse design and the system selected. Park (1996) evaluates several kinds of systems for equipment selection and finds that there are limitations on existing systems for material handling equipment selection.

After an extensive literature review, Rouwenhorst, et al. (2000) have indicated that the number of publications concerning design problems on strategic level appears to be limited. This is unfortunate since most costs of a warehouse are determined at an early stage. The results of a recent detailed survey of the research on warehouse design performed by Gu, et al. (2010) identify only few articles related to storage equipment selection, an important step in the warehouse design process. The storage equipment selection decision determines an appropriate automation level for the warehouse, and identifies equipment types for storage and retrieval. They emphasize that research on equipment selection is limited but important since it affects the whole warehouse design and the overall lifetime costs. According to Rouwenhorst, et al. (2000), the reason for this research gap on storage system selection is the large set of alternatives that are available. Due to the lack of tools available to assist the material handling design engineers in the selection of an appropriate, cost-effective storage system, designers are faced with three choices: (1) relying on handbooks and their own experience, (2) relying on the experience of equipment vendors and (3) employing consultants (Chan, et al., 2001). All of these options may not ensure a cost-effective and optimal solution to the choice of a warehouse storage system. Thus, this paper uses an Excel®-based DSS to select the most suitable type of storage system with the lowest investment and operational costs given the storage capacity and throughput.

## *3. Warehouse Storage Systems and Research Design*

In this section, the warehouse storage systems implemented in DSS are first discussed. Then, the performance measures are explained and the research design is presented.

### Warehouse Storage Systems

Modern warehousing systems can be classified as manual or automated (Bowersox et al. 2007). A combination of labor and handling equipment is utilized in manual systems, to facilitate receiving, processing and/or shipping. Automated systems on the on the other hand, attempt to minimize the labor as much as possible by substituting equipment capital investment (Ashayeri & Gelders, 1985). The use of manual systems is most common, but the use of fully automated systems is increasing. In this research, the focus is on manual storage and crane-based automated systems. The systems that are evaluated in this study are listed in Appendix II and will be discussed in detail hereafter.

#### 3.1.1. Manual Systems

In manual systems, a shelf rack is used for storing small parts. Shelf rack offers flexibility in the type and quantity of goods stored. However, it is not a space-efficient storage system. Cubic space utilization within a typical installation is often less than 50 percent resulting in increased operational warehouse costs (Tompkins and Smith, 1998). A case flow rack is a special kind of shelving with shelves tilted with rollers, to bring cases forward for picking. As only one case of a product needs to be on the pick face, a lot of products are available in a small area which means high SKU-density and an increase of picks/person-hour (Bartholdi and Hankman, 2011). A pallet rack consists of a metal frame with horizontal beams on which the pallets can rest (Van den Berg, 2007). Mobile racking systems are pallet racking systems mounted on heavy-duty bases, which are electrically driven on tracks mounted into the floor slab. (Anon, 2015).

### 3.1.2. Crane-based Automated Systems

An automated storage and retrieval system (AS/RS) is a product to picker storage system that consists of one or multiple parallel aisles with two high bay pallet racks alongside each aisle. A storage/retrieval machine travels within the aisle and performs storages and retrievals (Van den Berg and Gademann 2000). AS/RSs have been widely studied and used in distribution and production environments (Linn and Wysk, 1987). A unit-load AS/RS is used to store and retrieve pallet loads stored in single-deep racks. Double deep AS/RS storage is a unit-load system with two loads per row. Deep-lane storage is another variation on the unit load system where items are stored in a multi-deep storage with up to 10 loads per row, leading to a higher density of stored items (Bowersox, et al., 2007, Zaerpour, et al., 2015). A miniload AS/RS is a system that is designed for the storage and retrieval of small items stored in bins or drawers (Van den Berg and Gademann, 2000).

### 3.1.3. Performance Evaluation

Performance evaluation is important for both warehouse design and operation. Rouwenhorst, et al. (2000) find the prominent design criteria for a warehouse to be the storage capacity and the maximum throughput reached at minimum investment and operational costs. Evaluating the performance of a warehouse according to any of these design objectives can help the warehouse designer in evaluating the many design alternatives and narrow down the design space in an early stage, saving costs in the rest of the process. Within this research, the criteria of Rouwenhorst, et al. (2000) are taken as a guideline to evaluate different warehouse storage systems. We consider investment and operational costs of activities that are directly related to storing and retrieving operations, since such operations are significant in automated and manual systems. The costs of other activities such as administration and crossdocking are not considered in the calculations.

Research Design

This paper uses the approach illustrated in Figure 1 developed by Mitroff, et al., (1974). The approach consists of five consecutive phases: conceptualization, modeling, model solving, implementation, and validation.

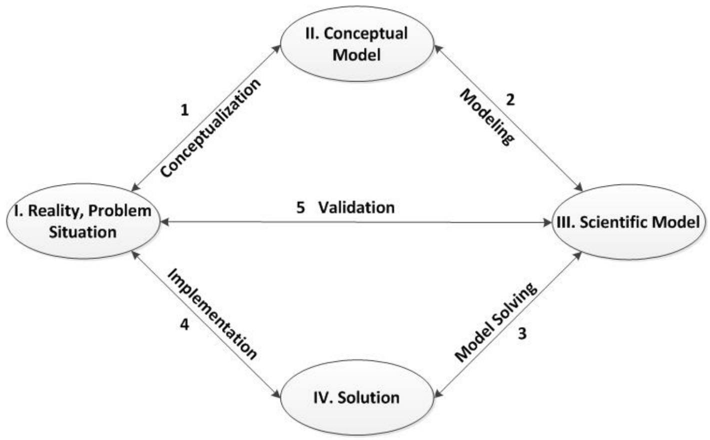



**Figure 1.** Five phase research methodology of the paper

In research, the scientific inquiry starts at stage I, the existence of a problem situation. The first phase of problem solving starts with the conceptualization, which results in the formulation of a conceptual model of the problem situation. The conceptual model gives a broad view of the problem and specifies the variables that define the nature of the problem and how these variables will be treated. Once the conceptual model has been formed, a scientific model from can be constructed based on the previous conceptual model. This can be done by mathematically modeling all the variables and their parameters. Solving the scientific model will lead to the solution stage which gives the outcome of the mathematical model. In the implementation phase the solution is then fed back to the problem situation for the purpose of taking action on it. Finally, to complete the model, an extra phase is added which is the validation phase. This phase determines the degree of correspondence between reality and the scientific model. In other words, this phase optimizes the model by adjusting the variables and parameters of the scientific model in such way that this will lead to a better solution and implementation.

The first three phases of the model developed by Mitrofet al. (1974) include conceptualization, modeling, and model solving. These steps have been vastly used in the literature in estimating the expected travel time for different storage systems (see e.g. Roodbergen, et al., 2008, Hausman, et al., 1976, and Zaerpour et al., 2015). The results of such papers have been used as input in our decision support system to calculate the expected travel time and throughput. Unlike the first three steps, the last two steps of the model (DSS implementation and cost comparison, validation and managerial evaluation) have been ignored in the literature while it has the highest importance for practice. Thus, this paper bridges this gap in the literature by using the decision support system to compare different storage systems based on investment and operational costs while a certain level of storage capacity and throughput is achieved.

In this research, first the practical implementation is executed by running the model using two main input parameters, throughput and storage capacity. For both parameters, a practical range is considered and within that range the investment and operational costs of each storage system is calculated in the DSS. The validation phase is executed by evaluating the DSS and the outcomes of the implementation phase. Managerial feedback is used for possible adjustment of parameters in the DSS. The specific research approach and steps that are used in these two stages are shown in Figure 2.

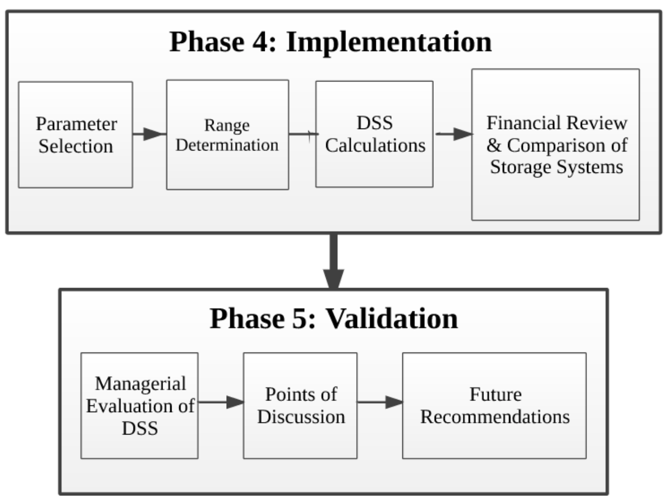



**Figure 2.** Research approach for DSS implementation and validation

A schematic overview of the DSS is given in Figure 3 which includes three main stages. The input parameters are entered in the input stage by a user. This is followed by the configuration phase in which DSS allows the user to evaluate the storage system for a given configuration and compare different storage systems using the outputs of the Excel®-based DSS (investment and operational costs). The storage capacity and throughput of a warehouse are the main factors that mainly determine the suitable type of storage system (i.e., manual or automated) for the warehouse which consequently impact the investment and operational costs. In order to decide whether storage capacity and throughput are met and how costs are estimated, other input parameters including travel times are required. For each storage system, Table 1 gives the reference from the literature which is used to estimate the travel time. In addition, Table 1 illustrates the mains inputs of DSS which are used for layout optimization and the main outputs of the DSS which are used to compare different storage systems. The detailed formulas used for cost calculations (implemented in Microsoft Excel®-based DSS) are illustrated in Appendix I.

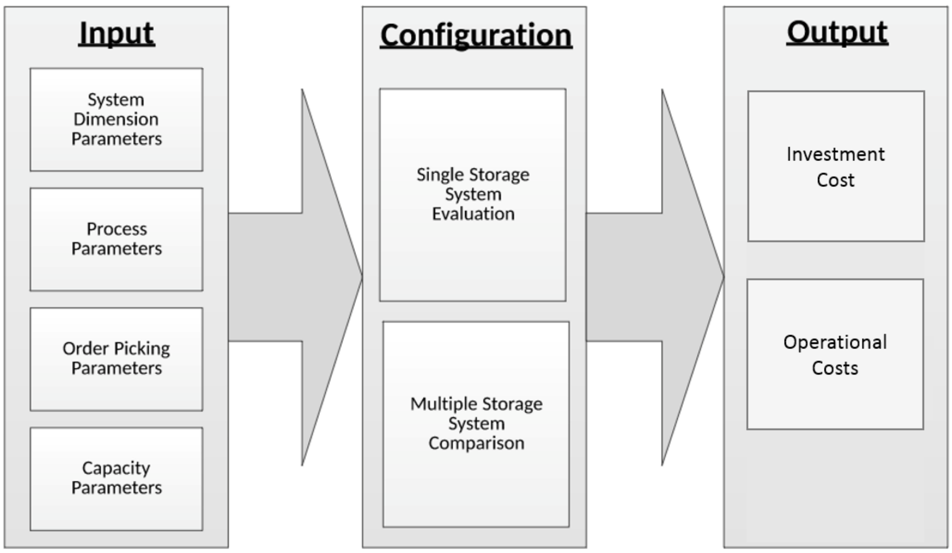



**Figure 3.** A schematic overview of DSS

**Table 1.** A methodology summary of Excel®-based DSS

| Storage System | Travel Time Estimation Paper | Investment Costs Formulas* | Operational Costs Formulas* | Design Inputs for System Comparison | DSS Outputs (Investment and Operational Cost Elements) |
|---|---|---|---|---|---|
| Shelf Racks | Roodbergen, et al. (2008) | (1) | (2) | Throughput capacity (cases/day), Storage Capacity (# case locations) | Investment cost (€), Depreciation cost (€), Maintenance cost (€), Interest cost (€), Personnel cost (€)** |
| Miniload AS/RS | Hausman, et al. (1976) | (3) | (4) | | |
| Case Flow Racks | Roodbergen, et al. (2008) | (5) | (6) | | |
| Single-deep & Double-deep AS/RS | Hausman, et al. (1976) | (7) | (8) | Throughput capacity (pallets/day), | |

| Storage System | Travel Time Estimation Paper | Investment Costs Formulas* | Operational Costs Formulas* | Design Inputs for System Comparison | DSS Outputs (Investment and Operational Cost Elements) |
|---|---|---|---|---|---|
| Pallet Racks (Wide+Narrow) | Roodbergen, et al. (2008) | (9) | (10) | Storage Capacity (# pallet locations) | |
| Deep-lane Compact Storage | Zaerpour, et al. (2015) | (11) | (12) | | |
| Mobile Racking | Monte Carlo Simulation | (13) | (14) | | |

Notes: *the formulas are given in Appendix I; ** personnel cost is considered for manual systems

## *4. Findings and Managerial Implications*

This section discusses the findings and managerial implications obtained from DSS. Section 4.1 focuses on the parameter selection, range determination, and calculation. Then, in Section 4.2, the financial review and comparison of storage systems are discussed. Finally, Section 4.3 concludes the section by explanting the managerial implications of the DSS outputs.

### 4.1. Implementation of DSS

This section discusses the implementation of DSS, in particular the selection and range determination of input parameters and output calculations.

#### 4.1.1. Parameter Selection and Range Determination

The aim of our numerical analysis is to obtain insights for small, medium and large size storage systems in terms of storage capacity and throughput. Thus, the range for storage capacity and throughput (as shown in Table 2) is selected from the literature such that it covers all three levels (see Bartholdi and Hackman, 2017, De Koster, 1996). The different storage systems that are evaluated, the storage unit and the ranges of the storage capacity and throughput are given in Table 2. Calculations are executed in the DSS in which the throughput and capacity are adjusted in steps. The steps (increments) in which the input parameters are adjusted are also shown in Table 2.

**Table 2.** Range for storage capacity and throughput

| Storage System | Storage Unit | Storage Capacity | Throughput Capacity |
|---|---|---|---|
| Shelf racks<br>Miniload AS/RS<br>Case Flow Racks | Cases/Bins | 10,000 – 200,000<br># Case Locations<br>Step: 10,000 | 1,000 – 20,000<br># Cases/Day<br>Step: 1,000 |
| Pallet Racks (Wide+Narrow)<br>Single-deep AS/RS<br>Double-deep AS/RS<br>Deep-lane compact storage<br>Mobile Racking | Pallets | 1,000 – 30,000<br># Pallet Locations<br>Step: 1,000 | 200 – 4,000<br># Pallets/Day<br>Step: 200 |

#### 4.1.2. Outputs of Calculations

The outputs are the operational and investment costs of each storage system. The mathematical construction of these performance criteria are illustrated in Appendix I. The operational costs can be further categorized into depreciation costs, maintenance costs, interest, and personnel costs. While the investment cost can be further specified into building and land costs, costs for the storage method (i.e. pallet racks) and costs for automated machines and conveyers. Figure 4 gives an overview of the consecutive steps in the decision support system for investment and operational cost calculation based on the required storage capacity and throughput.

Output of the calculations are summarized in two Excel® sheets, one for the case/bin and one for the pallet storage systems. To give a better overview, the results are compiled in a dynamic Excel® sheet in which the throughput and capacity can be manually adjusted and a table shows the results of all systems. The 2.5 deep AS/RS system is a name used in the DSS and is referred to double-deep AS/RS system in this paper.

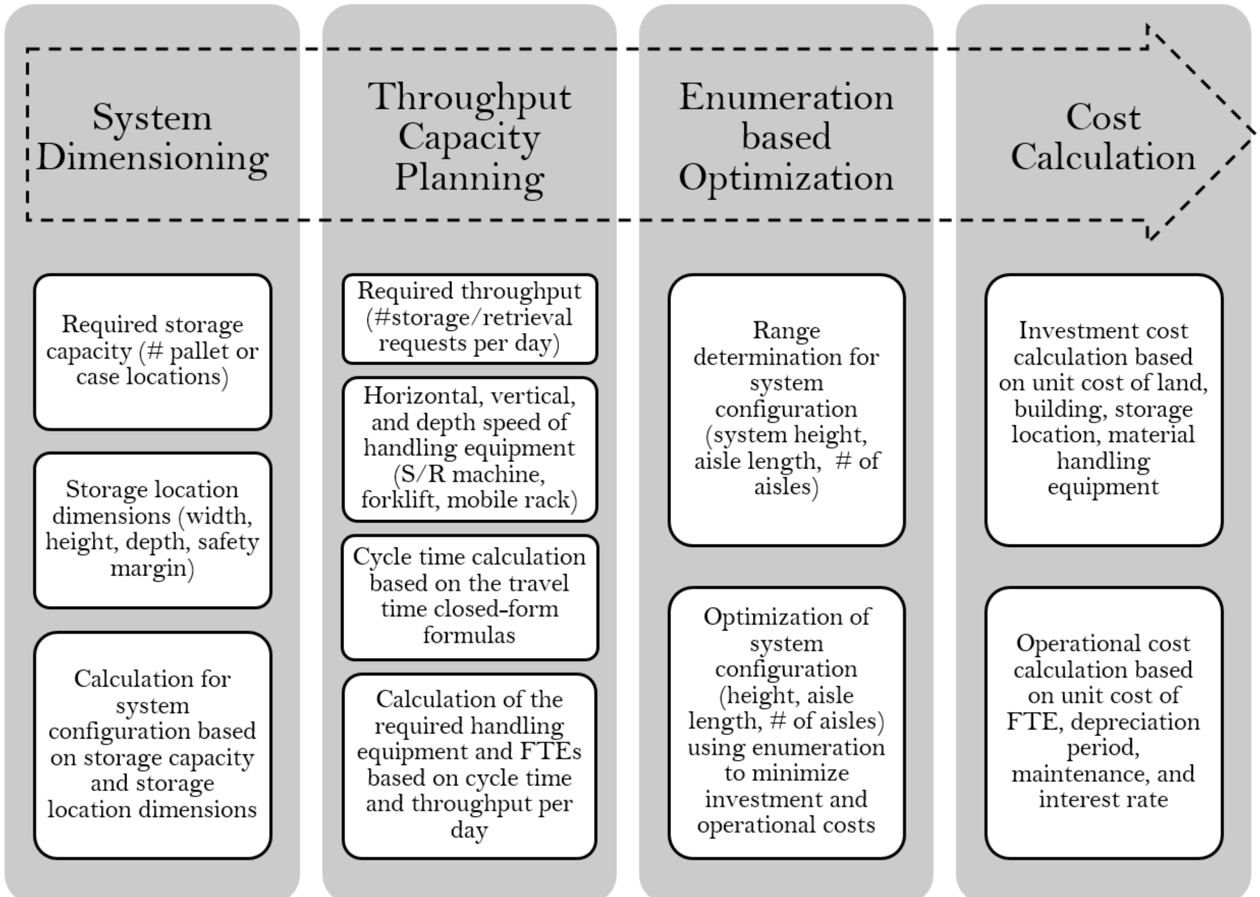


**Figure 4**. Consecutive steps of investment and operational cost calculation in the DSS

Using these Excel® DSS, numerical analyses have been performed and the results are presented in the next section. Furthermore, financial results obtained from such analyses are used to develop managerial insights for the warehouse design.

## 4.2. Financial Review and Comparison of Storage Systems

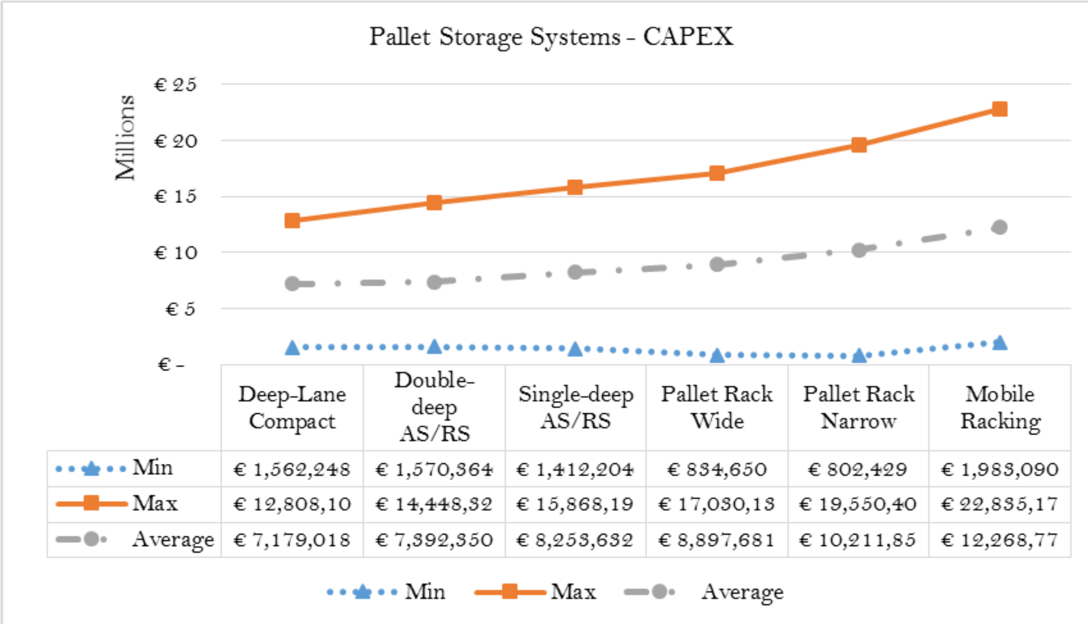
In this section, the results obtained from the DSS are discussed. First, the investment and operational costs of each system are investigated and the findings are discussed. Second, all results are summarized in a total cost overview for comparison purposes.

#### 4.2.1. Investment Costs Analysis

This section takes a detailed look at the investment costs of the pallet storage and case storage systems. Figures 5 and 6 show the minimum, maximum and average investment costs that are calculated by the DSS given the range of storage throughput and storage capacity shown in Table 2.

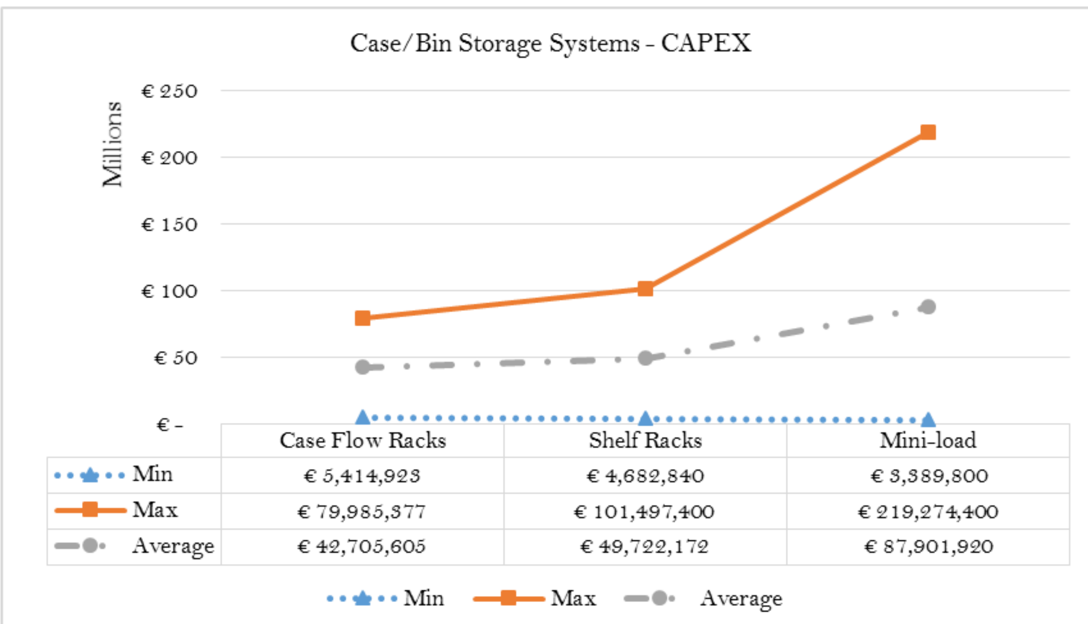
The results for pallet storage systems show that it within the group of automated pallet systems there is little variation in costs among the systems. This effect is also visible within the group of narrow and wide pallet rack systems. On the other hand, difference in costs do exist between the groups of automated and manual pallet rack systems. Minimum costs of the systems are lower for manual systems than for crane-based automated systems. The reason is the higher investment that the automated systems require compared to the manual systems. However, this is only the case when storage capacity and throughput are low. As soon as storage capacity and throughput increase, the costs for automated pallet systems become lower than for manual pallet systems. For manual systems with high storage and throughput capacity, potentially high investment in material handling equipment, land and building is required. This can be seen in Figure 5 with higher maximum costs for the manual pallet systems compared to the automated pallet systems. Investment costs for the mobile racking systems show to be the highest among all pallet systems, which could be due to the fact that these systems are very specific in their use and are not very efficient.

The results of the case systems are shown in Figure 6. The costs of the miniload systems are higher than for the other two systems. This can be explained due to the fact that the miniload systems are automated systems and use make use of cranes. Consequently, this requires a much higher initial investment compared to the manual systems.




| | Deep-Lane Compact | Double-deep AS/RS | Single-deep AS/RS | Pallet Rack Wide | Pallet Rack Narrow | Mobile Racking |
|---|---|---|---|---|---|---|
| Min | € 1,562,248 | € 1,570,364 | € 1,412,204 | € 834,650 | € 802,429 | € 1,983,090 |
| Max | € 12,808,10 | € 14,448,32 | € 15,868,19 | € 17,030,13 | € 19,550,40 | € 22,835,17 |
| Average | € 7,179,018 | € 7,392,350 | € 8,253,632 | € 8,897,681 | € 10,211,85 | € 12,268,77 |

**Figure 5.** Investment cost of pallet storage systems with varying capacity and throughput
*Note. Min = minimum costs for each system Max = maximum costs for each system, Average = average costs for each system, Equations (7), (9), (11), and (13) from Appendix I are used to calculate these results*




| | Case Flow Racks | Shelf Racks | Mini-load |
|---|---|---|---|
| Min | € 5,414,923 | € 4,682,840 | € 3,389,800 |
| Max | € 79,985,377 | € 101,497,400 | € 219,274,400 |
| Average | € 42,705,605 | € 49,722,172 | € 87,901,920 |

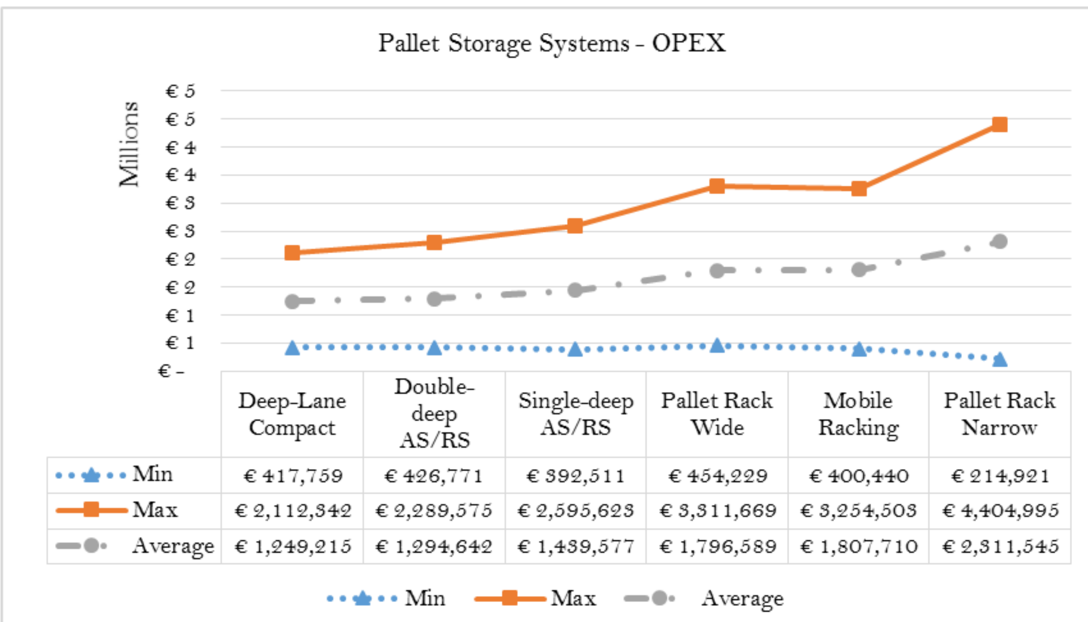
**Figure 6.** Investment costs of pallet storage systems with varying capacity and throughput
*Note. Equations (1), (3), and (5) from Appendix I are used to calculate these results*

### 4.2.2. Operational Costs Analysis

This section investigates the operational costs of the pallet storage and case storage systems. Figures 7 and 8 show the minimum, maximum and average operational costs that are calculated by the DSS given the range of throughput and storage capacity illustrated in Table 2.

Figure 7 shows that the operational costs for all automated pallet systems are approximately within the same range. The mobile racking systems and manual pallet systems are higher in operational costs than the automated systems. This is mainly due the fact that these systems are less efficient with higher levels of capacity and throughput resulting in an increase in personnel costs.

As Figure 8 shows, among the case systems, the operational costs of shelf racks increase rapidly when the throughput and storage capacity increase. This is due to the fact that shelf racks become less efficient for larger warehouses (longer travel times, higher personnel).




| | Deep-Lane Compact | Double-deep AS/RS | Single-deep AS/RS | Pallet Rack Wide | Mobile Racking | Pallet Rack Narrow |
|---|---|---|---|---|---|---|
| Min | € 417,759 | € 426,771 | € 392,511 | € 454,229 | € 400,440 | € 214,921 |
| Max | € 2,112,342 | € 2,289,575 | € 2,595,623 | € 3,311,669 | € 3,254,503 | € 4,404,995 |
| Average | € 1,249,215 | € 1,294,642 | € 1,439,577 | € 1,796,589 | € 1,807,710 | € 2,311,545 |

**Figure 7.** Operational costs of pallet storage systems with varying capacity and throughput
*Note. Equations (8), (10), (12), and (14) from Appendix I are used to calculate these results*

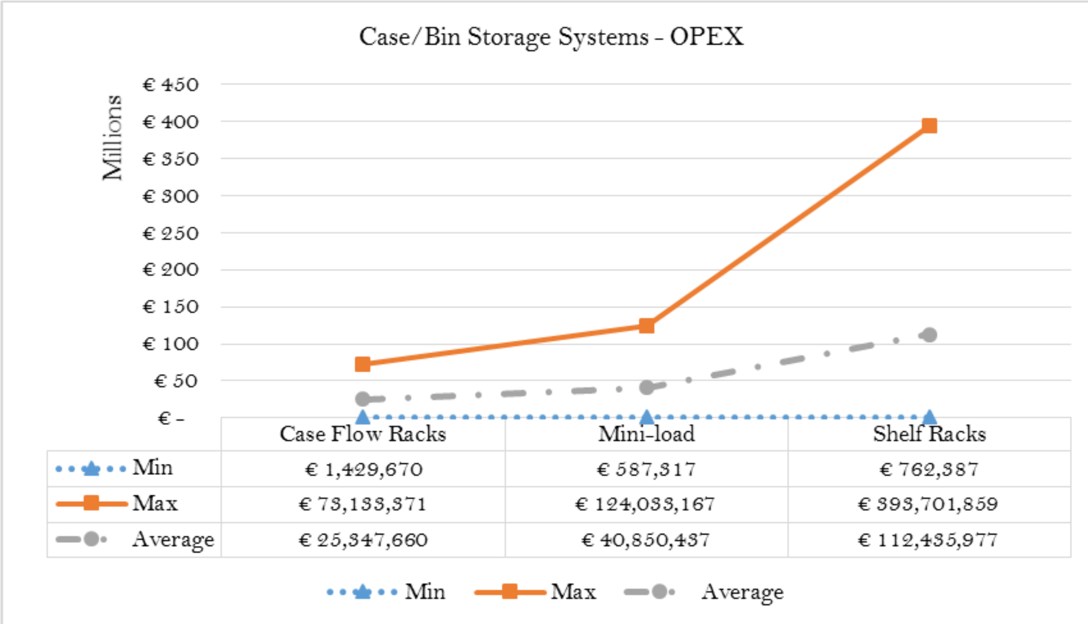
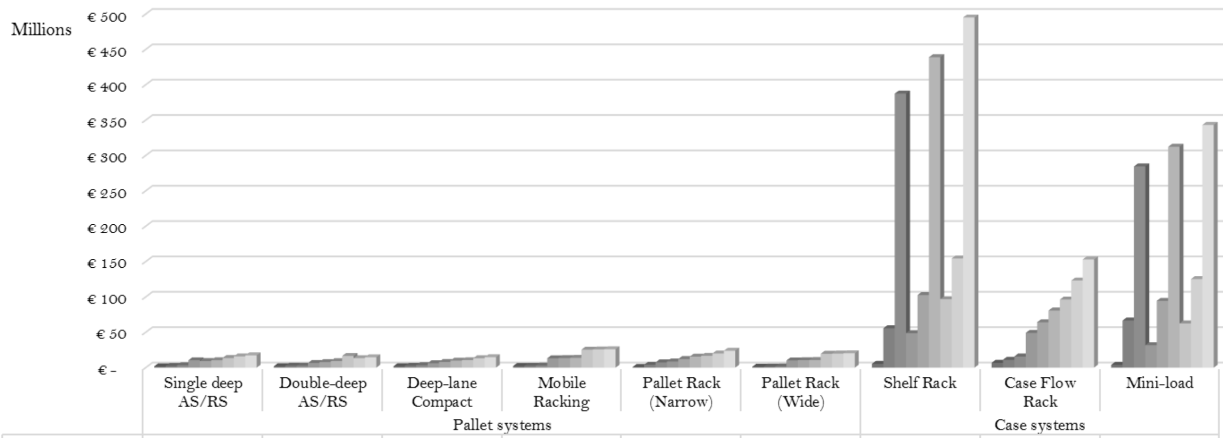



**Figure 8.** Operational costs of case/bin storage systems varying capacity and throughput range
*Note. Equations (2), (4), and (6) from Appendix I are used to calculate these results*

### 4.2.3. Total Storage System Cost Overview

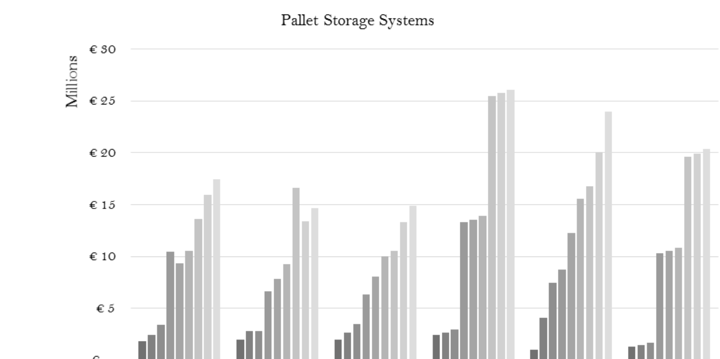
This section combines the results of the previous two sections by showing the total cost of each system for a combination of low, medium and high levels of throughput and capacity (see Figure 9(a)). In order to highlight the difference in the total costs of pallet and case storage systems, Figures 9(b) and (c) show the total costs separately for pallet and case systems. It should be noted that operational costs are incurred annually while the investment costs are one-time costs.

These results show that among the pallet systems, the manual pallet racks are the cheapest systems when storage capacity is low. Because these pallet racks are only single deep and minimum investment in equipment is required to achieve the desired throughput and storage capacity. It can be seen that when capacity increases, there is a need for much more compact systems that can stock more pallets in a smaller space. Hence, double-deep AS/RS and deep-lane compact storage systems are the systems with the lowest costs for medium to high capacity levels. Results among the case systems show that system costs increase rapidly with an increase of the throughput in particular for miniload systems.



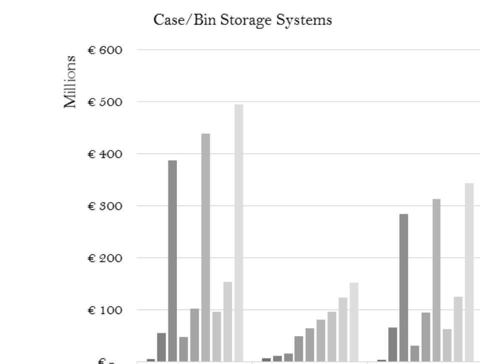

| | Single deep AS/RS | Double-deep AS/RS | Deep-lane Compact | Mobile Racking | Pallet Rack (Narrow) | Pallet Rack (Wide) | Shelf Rack | Case Flow Rack | Mini-load |
|---|---|---|---|---|---|---|---|---|---|
| | Pallet systems | | | | | | Case systems | | |
| Low Low | € 1,804,715 | € 1,997,135 | € 1,980,007 | € 2,383,530 | € 1,017,350 | € 1,288,879 | € 5,445,227 | € 6,844,594 | € 3,977,117 |
| Low Medium | € 2,390,738 | € 2,783,872 | € 2,681,636 | € 2,664,179 | € 4,101,762 | € 1,453,879 | € 55,738,081 | € 11,134,594 | € 66,705,432 |
| Low High | € 3,413,923 | € 2,783,872 | € 3,506,356 | € 2,976,012 | € 7,447,313 | € 1,673,879 | € 387,638,795 | € 15,892,094 | € 284,705,874 |
| Medium Low | € 10,440,857 | € 6,589,100 | € 6,298,139 | € 13,278,593 | € 8,760,184 | € 10,277,292 | € 48,791,338 | € 49,210,437 | € 31,750,432 |
| Medium Medium | € 9,361,004 | € 7,847,696 | € 8,042,902 | € 13,568,584 | € 12,223,100 | € 10,552,292 | € 102,635,338 | € 64,225,437 | € 94,478,746 |
| Medium High | € 10,496,419 | € 9,263,731 | € 9,967,843 | € 13,890,796 | € 15,583,314 | € 10,827,292 | € 439,086,052 | € 80,890,437 | € 312,479,189 |
| High Low | € 13,642,256 | € 16,586,007 | € 10,531,862 | € 25,455,428 | € 16,733,727 | € 19,626,804 | € 96,841,402 | € 96,303,748 | € 62,578,810 |
| High Medium | € 15,924,183 | € 13,383,837 | € 13,306,864 | € 25,755,860 | € 20,038,942 | € 19,956,804 | € 154,430,259 | € 123,226,248 | € 125,307,125 |
| High High | € 17,424,097 | € 14,694,912 | € 14,857,114 | € 26,089,674 | € 23,955,400 | € 20,341,804 | € 495,199,259 | € 153,118,748 | € 343,307,568 |

(a) Pallet and Case storage systems





| | Single deep AS/RS | Double-deep AS/RS | Deep-lane Compact | Mobile Racking | Pallet Rack (Narrow) | Pallet Rack (Wide) |
|---|---|---|---|---|---|---|
| Low Low | € 1,804,715 | € 1,997,135 | € 1,980,007 | € 2,383,530 | € 1,017,350 | € 1,288,879 |
| Low Medium | € 2,390,738 | € 2,783,872 | € 2,681,636 | € 2,664,179 | € 4,101,762 | € 1,453,879 |
| Low High | € 3,413,923 | € 2,783,872 | € 3,506,356 | € 2,976,012 | € 7,447,313 | € 1,673,879 |
| Medium Low | € 10,440,857 | € 6,589,100 | € 6,298,139 | € 13,278,593 | € 8,760,184 | € 10,277,292 |
| Medium Medium | € 9,361,004 | € 7,847,696 | € 8,042,902 | € 13,568,584 | € 12,223,100 | € 10,552,292 |
| Medium High | € 10,496,419 | € 9,263,731 | € 9,967,843 | € 13,890,796 | € 15,583,314 | € 10,827,292 |
| High Low | € 13,642,256 | € 16,586,007 | € 10,531,862 | € 25,455,428 | € 16,733,727 | € 19,626,804 |
| High Medium | € 15,924,183 | € 13,383,837 | € 13,306,864 | € 25,755,860 | € 20,038,942 | € 19,956,804 |
| High High | € 17,424,097 | € 14,694,912 | € 14,857,114 | € 26,089,674 | € 23,955,400 | € 20,341,804 |



| | Shelf Rack | Case Flow Rack | Mini-load |
|---|---|---|---|
| Low Low | € 5,445,227 | € 6,844,594 | € 3,977,117 |
| Low Medium | € 55,738,081 | € 11,134,594 | € 66,705,432 |
| Low High | € 387,638,795 | € 15,892,094 | € 284,705,874 |
| Medium Low | € 48,791,338 | € 49,210,437 | € 31,750,432 |
| Medium Medium | € 102,635,338 | € 64,225,437 | € 94,478,746 |
| Medium High | € 439,086,052 | € 80,890,437 | € 312,479,189 |
| High Low | € 96,841,402 | € 96,303,748 | € 62,578,810 |
| High Medium | € 154,430,259 | € 123,226,248 | € 125,307,125 |
| High High | € 495,199,259 | € 153,118,748 | € 343,307,568 |


(b) Pallet storage systems

(c) Case/Bin storage systems

**Figure 9.** Storage System Cost Overview – Total system costs in Euros

*Note. In each row, the capacity and throughput are indicated in a sequence. For example, on the second line, (Low Medium) indicates that the capacity is Low and the throughput is Medium.*

*In the pallet storage systems, for capacity, Low, Medium, and High indicate 1,000, 15,000 and 30,000, respectively. For throughput, Low, Medium, and High indicate 200, 2,000 and 4,000, respectively.*

*In the case/bin storage systems, for capacity, Low, Medium, and High indicate 10,000, 100,000 and 200,000, respectively. For throughput, Low, Medium, and High indicate 1,000, 10,000 and 20,000, respectively.*

### 4.3. Validation of the DSS

The validation phase is executed by evaluating the DSS and the outcomes of the implementation in practice in collaboration with material handling experts (managers and engineers). Since, the DSS is used at the design phase, it can be validated by comparing the results (investment and operational costs) with the cost of a real storage system after it is implemented. Since there exists no public data on the investment and operational costs of storage systems given throughput and storage capacity, using material handling experts was the viable option to validate the results. Thus, the team of material handling managers and engineers from two leading European material handling suppliers have confirmed the results based on their past confidential projects. Due to confidentiality, the names of these companies cannot be revealed.

Detailed cost results in Figure 9 on the automated pallet rack systems show that for a lower storage capacity and lower throughput, the single-deep AS/RS system gives the lowest overall costs. When the capacity and throughput increase, the deep-lane compact and double-deep AS/RS become the systems with the lowest costs. This effect is expected due to the fact that the last two systems are more efficient resulting in a higher storage utilization, thus requiring less investment costs. One of the key discussion points is that this relation is not entirely correct due to a correction needed on the storage capacity input parameter. Currently, the DSS takes the number of pallet locations as a capacity parameter for automated pallet systems. However, the number of pallet locations does not correspond completely to the number of pallets that can be stored due to the fill-rate (storage location utilization) of pallet systems. In most cases, for single deep AS/RS systems, the storage locations are almost fully utilized while for multi-deep AS/RS storage systems, on average half of storage locations are utilized. Thus, this factor should be taken into account when comparing the costs among the different automated pallet storage systems.

The DSS divides the systems into two types of storage units, pallets and cases. Looking at the pallet systems used in practice, it can be seen that such a division is not always the case. Some systems always use full pallets such as deep-lane compact storage system, double-deep storage systems and the mobile racking systems, meaning that only a full pallet can be stored or retrieved in the system. However, other systems such as single deep AS/RS systems and manual pallet racks are also designed to handle a mix of pallets and cases, meaning that it is also possible to retrieve single cases from pallets. Having this functionality within the DSS would make it better adjusted to practical situations. However, adding this functionality in the system can also be difficult. This is due to the fact that throughput for pallet systems will be hard to measure when case storage and retrievals are also included in the calculation.

Selecting the appropriate type of warehouse storage system is not an isolated activity. Choosing the right type of warehouse storage system is a complex task due to the large set of alternatives available and different storage strategies that exist and can be combined in multiple ways; e.g. warehouses may have three or more types of warehouse storage systems they may use multiple storage strategies (Rouwenhorst, et al., 2000). A shortcoming of the DSS in this research is that it is not able to calculate the total costs of a multiple storage system configuration, which is more common in practice than choosing just a single storage system. However, enumeration of all feasible designs in order to find the optimal solution is often practically impossible. Consequently, the DSS can function as a guide to a warehouse manager to inform them on possible costs of each warehouse system and to compare these costs between.

## *5. Conclusions and Future Research*

The literature shows that there is a large gap between the academic world and practice of warehouse design. This research tries to bridge this gap by providing insights that enable managers to select the best type of storage system considering the investment and operational costs given throughput and storage capacity. A DSS is designed which considers different scenarios for a range of storage capacity and throughput resulting in investment and operational cost calculation per scenario per storage system.

The DSS is evaluated in by experts within the field of warehouse design in order to make the model better fit in practice. The results show that among the pallet warehouses, the manual pallet racks are the cheapest systems when the storage capacity and throughput are low. Double-deep automated and deep-lane compact storage systems are the systems with the lowest investment and operational costs for medium to high capacity levels. The results for the case warehouses show that system investment and operational costs increase with an increase in the throughput and storage capacity. This increase in more significant for miniload AS/RS considering the investment costs and for shelf-racks considering the operational costs.

To improve the DSS, first, a closer look should be taken at the combination of pallets and cases for systems such as manual pallet racks. Moreover, this research focuses on the implementation and validation of a DSS by only varying the storage capacity and throughput. However, these parameters are linked to all smaller input parameters of each storage system and are the ones that directly have influence on the system outputs. Validation of all input parameter will be time consuming and should be done theoretically as well as evaluating them in practice with multiple kinds of management parties. Nonetheless, this will improve the DSS and will result in accurate outputs of the system.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*Appendix I: Investment and operational costs calculation for each storage system*

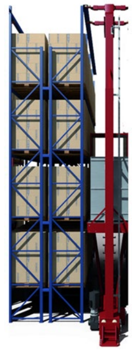
| Parameter | Explanation | Unit |
|---|---|---|
| | | |
| $I$ | Investment Costs | € |
| $O$ | Operational Costs | € |
| $D$ | Depreciation Costs | € |
| $M$ | Maintenance Costs | € |
| $R$ | Interest Costs | € |
| $P$ | Personnel Costs | € |
| | | |
| $\alpha$ | Surface Area | $m^2$ |
| $\beta$ | Price per Unit | € |
| $\gamma$ | Quantity of Units | unit |
| $\delta$ | Depreciation Period | years |
| $\theta$ | Maintenance Percentage | % |
| $\varepsilon$ | Interest Percentage | % |
| $\eta$ | FTEs needed | unit |
| $\lambda$ | Yearly costs per FTE | € |
| $\kappa$ | Length | m |
| $\rho$ | Depreciation rest value | € |
| | | |
| $b$ | Building | |
| $g$ | Ground | |
| $sr$ | Shelf Racks | |
| $t$ | Trolleys | |
| $pr$ | Pallet Racks | |
| $rt$ | Reach Trucks | |
| $irt$ | Initial Investment Reach Trucks | |
| $opt$ | Order Picking Trucks | |
| $srm$ | S/R machine | |
| $isrm$ | Initial Investment S/R machine | |
| $cr$ | Conduction Rails | |
| $c$ | Conveyer | |
| $n$ | Nodes | |
| $ops$ | Order Picking Stations | |
| $mr$ | Miniload Racks | |
| $mc$ | Miniload Crane | |
| $iss$ | Inbound (Storage) Station | |
| $oss$ | Outbound (Storage) Station | |
| $f$ | Floors | |
| $s$ | Sorter | |
| $l$ | Lift | |
| $cfr$ | Case flow racks | |
| $psc$ | Picking Station Conveyer | |
| $sl$ | Shuttle | |

| Calculation Formulas | Eq. no. | Calculation Formulas | Eq. no. |
|---|---|---|---|
| ***Shelf racks***<br>*Investment Costs*<br>$I = \sum I_i$ *for i = b, g, sr, t*<br>$I_i = \alpha_i * \beta_i$ *for i = b, g*<br>$I_i = \gamma_i * \beta_i$ *for i = sr, t* | **(1)** | ***Single-Deep AS/RS & Double-Deep AS/RS***<br>*Operational Costs*<br>$O = D + M + R$<br>$D = \sum D_i$<br>$D_i = \frac{I_i}{\delta_i}$<br>$M = \sum M_i$<br>$M_i = I_i * \theta_i$ } *for i = b, pr, isrm, srm, cr*<br>$R = \sum R_i$<br>$R_i = I_i * \varepsilon * 0{,}5$ } *for i = b, g, pr, isrm, srm, cr* | **(8)** |
| ***Shelf racks***<br>*Operational Costs*<br>$O = D + M + R + P$<br>$D = \sum D_i$<br>$D_i = 0{,}5 * \frac{I_i}{\delta_i}$<br>$M = \sum M_i$<br>$M_i = I_i * \theta_i$ } *for i = b, sr, t*<br>$R = \sum R_i$<br>$R_i = I_i * \varepsilon * 0{,}5$ } *for i = b, g, sr, t*<br>$P = \eta * \lambda$ | **(2)** | ***Pallet Racks***<br>*Investment Costs*<br>$I = \sum I_i$ *for i = b, g, pr, rt, opt*<br>$I_i = \alpha_i * \beta_i$ *for i = b, g*<br>$I_i = \gamma_i * \beta_i$ *for i = pr, rt, opt* | **(9)** |
| ***Mini-load***<br>*Investment Costs*<br>$I = \sum I_i$ *for i = b, g, mr, mc, c, iss, oss, f, s, l*<br>$I_i = \alpha_i * \beta_i$ *for i = b, g, f*<br>$I_i = \gamma_i * \beta_i$ *for i = mr, mc, iss, oss, s, l*<br>$I_i = \kappa_i * \beta_i$ *for i = c* | **(3)** | ***Pallet Racks***<br>*Operational Costs*<br>$O = D + M + R + P$<br>$D = \sum D_i$<br>$D_i = \frac{I_i}{\delta_i}$<br>$M = \sum M_i$<br>$M_i = I_i * \theta_i$ } *for i = b, pr, rt, opt*<br>$R = \sum R_i$<br>$R_i = I_i * \varepsilon$ } *for i = b, g, pr, rt, opt*<br>$P = \eta * \lambda$ | **(10)** |
| ***Mini-load***<br>*Operational Costs*<br>$O = D + M + R + P$<br>$D = \sum D_i$<br>$D_i = \frac{I_i - \rho_i}{\delta_i}$ } *for i = b, mr, mc, c, iss, oss, f, s, l*<br>$M = \sum M_i$<br>$M_i = I_i * \theta_i$<br>$R = \sum R_i$ } *for i = b, g, mr, mc, c, iss, oss, f, s, l*<br>$R_i = I_i * \varepsilon * 0{,}5$<br>$P = \eta * \lambda$ | **(4)** | ***Deep-lane Compact Storage***<br>*Investment Costs*<br>$I = \sum I_i$ *for i = b, g, pr, isrm, srm, sl, cr*<br>$I_i = \alpha_i * \beta_i$ *for i = b, g*<br>$I_i = \gamma_i * \beta_i$ *for i = pr, isrm, srm, sl*<br>$I_i = \kappa_i * \beta_i$ *for i = cr* | **(11)** |

| | | | |
|---|---|---|---|
| ***Case Flow Rack***<br>*Investment Costs*<br>$I = \sum I_i$ *for i = b, g, cfr, c, ops, psc*<br>$I_i = \alpha_i * \beta_i$ *for i = b, g*<br>$I_i = \gamma_i * \beta_i$ *for i = cfr, ops, psc*<br>$I_i = \kappa_i * \beta_i$ *for i = c* | **(5)** | ***Deep-lane Compact Storage***<br>*Operational Costs*<br>$O = D + M + R$<br>$\left.\begin{array}{l} D = \sum D_i \\ D_i = \frac{I_i}{\delta_i} \\ M = \sum M_i \\ M_i = I_i * \theta_i \end{array}\right\}$ *for i = b, pr, isrm, srm, sl, cr*<br>$\left.\begin{array}{l} R = \sum R_i \\ R_i = I_i * \varepsilon * 0{,}5 \end{array}\right\}$ *for i = b, g, pr, isrm, srm, sl, cr* | **(12)** |
| ***Case Flow Rack***<br>*Operational Costs*<br>$O = D + M + R + P$<br>$\left.\begin{array}{l} D = \sum D_i \\ D_i = \frac{I_i - \rho_i}{\delta_i} \\ M = \sum M_i \\ M_i = I_i * \theta_i \end{array}\right\}$ *for i = b, cfr, c, ops, psc*<br>$\left.\begin{array}{l} R = \sum R_i \\ R_i = I_i * \varepsilon \end{array}\right\}$ *for i = b, g, cfr, c, ops, psc*<br>$P = \eta * \lambda$ | **(6)** | ***Mobile Racking***<br>*Investment Costs*<br>$I = \sum I_i$ *for i = b, g, pr, irt, rt*<br>$I_i = \alpha_i * \beta_i$ *for i = b, g*<br>$I_i = \gamma_i * \beta_i$ *for i = pr, irt, rt* | **(13)** |
| ***Single-Deep AS/RS & Double-Deep AS/RS***<br>*Investment Costs*<br>$I = \sum I_i$ *for i = b, g, pr, isrm, srm, cr*<br>$I_i = \alpha_i * \beta_i$ *for i = b, g*<br>$I_i = \gamma_i * \beta_i$ *for i = pr, isrm, srm,*<br>$I_i = \kappa_i * \beta_i$ *for i = cr* | **(7)** | ***Mobile Racking***<br>*Operational Costs*<br>$O = D + M + R + P$<br>$\left.\begin{array}{l} D = \sum D_i \\ D_i = \frac{I_i}{\delta_i} \\ M = \sum M_i \\ M_i = I_i * \theta_i \end{array}\right\}$ *for i = b, pr, irt, rt*<br>$\left.\begin{array}{l} R = \sum R_i \\ R_i = I_i * \varepsilon * 0{,}5 \end{array}\right\}$ *for i = b, g, pr, irt, rt*<br>$P = \eta * \lambda$ | **(14)** |

*Appendix II: Evaluated storage systems in the DSS*

| Storage System | Automation level | Description | Illustration |
|---|---|---|---|
| Shelf racks | Manual | Basic storage methods consisting of shelves and used for storage of small parts |  |
| Case flow racks | | Special kind of shelve, tilted with rollers |  |
| Pallet racks | | Metal frame with pallets used for storage of larger parts |  |
| Mobile racking | | Pallet racking system with movable aisles |  |
| Mini-load AS/RS | Automated (Crane-based) | AS/RS for small items with storage in drawers or bins |  |

| Storage System | Automation level | Description | Illustration |
|---|---|---|---|
| Single-deep AS/RS | | Unit load AS/RS in single-deep storage racks |  |
| Double-deep AS/RS | | Unit load AS/RS in double-deep storage racks |  |
| Deep-lane compact storage | | Unit load AS/RS in multi-deep storage racks |  |