Scenario-based Cycle Time Comparison of Cellular Transport Systems with Conventional Warehouse Systems

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Abstract- In today's business environment of rapidly changing customer demands, varying online order quantities, tight delivery schedules, and high customer service level requirements, it is becoming increasingly difficult for companies to achieve high performance standards using existing warehousing systems. The well-structured traditional warehouse system cannot meet the huge challenge of adapting requirements to today's global market which requires greater flexibility and faster operation capability in managing inventory. Alternative warehouse methodologies should be appropriate for the value added chain concept of companies, have enough flexibility to adapt to market conditions, and be strongly agile to overcome the late or no delivery risk. At this point, the Cellular Transport System (CTS) has been developed as an alternative system by the Fraunhofer Institute for Material Flow and Logistics. In this study, the comparison of CTS with conventional systems by using cycle time calculation is provided.

Keywords: cellular transport system, warehouse system, cycle time, spreadsheet modeling.

I. Introduction

Warehouse systems play an ever-increasing role in companies including impacting crucial operations points such as the on-time delivery of goods and service quality Automated Storage and Retrieval Systems (AS/RSs) have been widely used in distribution and production environments since their introduction in the 1950s. Between 1994 and 2004, there has been a significant increase in the number of AS/RSs used in distribution environments (Roodbergen and Vis, 2009).

An AS/RS is mostly utilized in distribution centers and production environments in order to store raw materials or (semi-) finished products in racks and to pick products requested by customers from storage to complete an order. An AS/RS is fully automated and can store or retrieve products without the assistance of a worker. Although these systems have several advantages over manual warehouse systems, such as providing accurate and effective handling of product, resulting in savings in both space and labor costs, their high installation and maintenance costs are a definite concern. In its most basic form, an AS/RS consists of storage racks served by cranes running through aisles between two racks where products or raw materials/components are stored and retrieved automatically.

Another novel warehouse system for automated handling is the Autonomous Vehicle Storage and Retrieval System (AVS/RS) which has been implemented at scores of facilities that reside primarily in Europe (Malmborg, 2002). Furthermore, this form of warehouse system has successfully been implemented at a particular French distribution center. The AVS/RS, explained by Ekren and Heragu (2011) in detail, has the capability to transport products not only within the same aisle but also from one tier to another by using lifts. In other words, autonomous vehicles travel horizontally over rails through aisles and vertically by utilizing elevators. In addition, the main advantage of this type of system is that autonomous vehicles are capable of traveling to other aisles in the case of need at those locations. Thus, they do not have to be bound to a specific aisle as typical AS/RS systems. Gagliardi, et al., (2011) detailed a study of an AVS/RS that was carried out in a French distribution center. This study was based on a strict application of a pure random storage assignment policy with the completion of orders according to a "first come, first serve" rule and a dwell-point policy (which means that autonomous vehicles remain in place after the completion of each transaction).

The AVS/RS system is composed of autonomous vehicles, lifts, conveyors, and storage racks. AVS/RSs utilize a rail system in order to operate in orthogonal directions within high-rise, high-density storage area. The storage area is divided into multiple tiers and each tier has a rail system (Ekren and Heragu, 2011).

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II. THEORETICAL BACKGROUND OF CTS

In recent years, research activities involving the Internet of Things (IoT) has examined decentralized control systems and their use in warehouse systems (Günthner and ten Hompel, 2010). The Cellular Transport System (CTS) is an example of a decentralized warehouse system that represents the application of IoT in the field of logistics. IoT includes the vision of creating a link between everyday objects through efficient information and communication technologies in order to enable new classes of applications and services. For instance; the RFID technology, one of the technological mainstays of IoT has numerous applications in warehouse systems. Hence, it is possible to change conventional centralized material flow systems using such technologies to decentralized material control systems.

According to a comprehensive definition provided by (ten Hompel and Heidenblut, 2011) "Cellular Transport Systems are based on material handling entities. These entities could be autonomous transport vehicles or autonomous conveying modules. The control and the communication between these autonomous entities are executed by Software Agents. Cellular Transport Systems are flexible in their topology, for this reason, they are able to adapt to environmental changes. Finally, this ensures the overall transport systems' performance due to the interaction between the material handling entities." The main principle behind the CTS concept is that decisions are made by the self-governing units that depend on gathered information or probabilistic calculations. Generally speaking, centralized control systems are losing their importance for warehouse management in favor of decentralized control systems. Kamagaew, et al., (2011) state that "hierarchical structures are dissolved towards a mesh-like structure with self-containing entities." In warehouse systems, autonomous units, each called a Multi Shuttle Move (MSM) unit, consist of a variety of functions the provide consistent communication and negotiation ability, high sensor/actuator properties to gather local information to ensure advanced flexibility, collision avoidance, and task assignment.

MSM is an integration of a standard shuttle's principle and an Automated Guided Vehicle (AGV) principle which has been implemented by scientists at Germany's Fraunhofer Institute for Material Flow and Logistics in an attempt to create a novel and effective kind of warehouse system. The MSM is not only capable of moving on a rail which is mounted in the storage rack, but is also able to leave the storage area and work as an AGV in other area using open path navigation. Currently, an experimental implementation of CTS was built on a 1000 square meters footprint with a 65 meter long test area in the Dortmund Fraunhofer IML in order to analyze its exact performance (Kirks, et al., 2012). The entire system, including 50 Multi-shuttle Move® units, 5 order picking stations and storage racks with elevators located two sides of storage, was implemented to examine the performance of CTS as compared with other conventional warehouse systems. The experimental implementation is depicted in Figure 1 below.
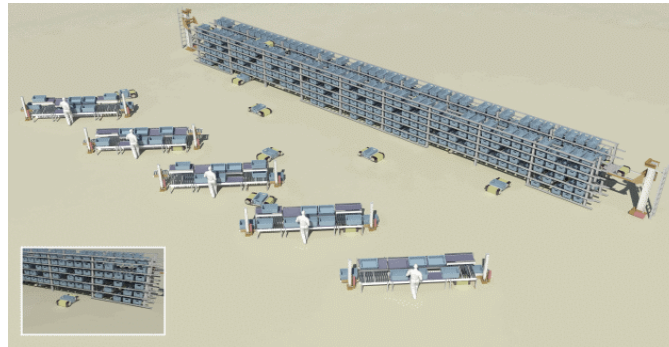

Fig. 1: The experimental area of Cellular Transport System with MSMs © Fraunhofer IML

III. CYCLE TIME CALCULATION

a) Automated Storage and Retrieval Systems (AS/RS)

With this type of automated system, one crane is in charge of carrying loads back and forth from storage areas. Also, a conveyor system is used to transport picked items to a packing workstation or onto the actual storage rack. Cycle time, the time it takes for a complete operation, is calculated using what is known as a single command rule. Single command entails that the crane or other transportation vehicle is performing single storage or a single retrieval operation. In order to gain a better understanding of cycle times, detailed explanations about storage and retrieval operations are provided as follows.

In the case of a storage cycle, the machine picks up a load, travels to the storage location, deposits the load, and returns empty to the Input/ Output station. Similarly, in a retrieval cycle, the Storage/ Retrieval machine begins at the Input/ Output station and travels empty to the retrieval location, picks up the load, moves to the Input/ Output station, and deposits the load there.

The view from the top of AS/RS is given in Figure 2. Bozer and White (1984) derived the basic cycle time expressions.
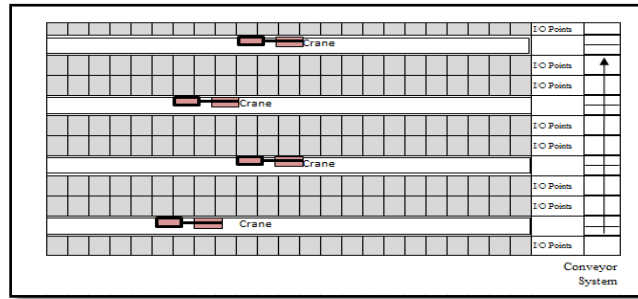

Fig. 2: The components of AS/RS configuration

From this basic system design, the following expression is derived in order to calculate cycle time for a single command transaction. The following equations are generated for a totally randomized storage policy. The notations and equations are given as follows:

$$\overline{T} = \max\left(\frac{L}{v_x}, \frac{H}{v_y}\right) \quad (1)$$

$$b = \frac{1}{T}\min\left(\frac{L}{v_x}, \frac{H}{v_y}\right) \quad (2)$$

$$E(SC) = \overline{T}\left(\frac{1}{3}b^2 + 1\right) \quad (3)$$

where;

v_x :   Horizontal velocity of S/R machine

v_y :   Vertical velocity of S/R machine
L :   Length of the rack
H :   Height of the rack
T :   Farthest travel time
b :   Shape factor
$E(SC)$:   Expected single-command round-trip travel time

b) *Autonomous Vehicle Storage and Retrieval Systems (AV/SRS)*

An AVS/RS utilizes a rail system. The storage area is divided into multiple tiers and each tier utilizes a rail system. The rail system allows vehicles to access any location on a tier (level) within the storage area. The configuration of AVS/RS is represented in Figure 3.
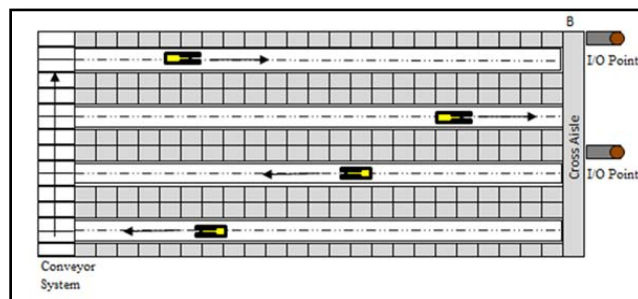

Fig. 3: The components of AVS/RS configuration

Fukunari and Malmborg (2008) derived a mathematical expression to calculate single command cycle time for an AVS/RS. The notations and equation are provided as follows:

$$E(SC) = 2\left\{\left[\frac{T-1}{T}\right]\left(t_h + \frac{1}{\mu_{lift}}\right) + \frac{t_h}{T} + \delta\right\} \quad (4)$$

where;

T :   Number of tiers
t_h :   Expected horizontal vehicle travel time
$1/\mu_{lift}$:   Expected lift cycle time.

δ :   Load transfer time between vehicles and   storage positions

c) *Cellular Transport System (CTS)*

In the CTS model, the shuttle moves horizontally with the help of a rail system between storage racks and vertically by means of lifts. The parameters and variables for these components are very crucial for the analytical model. The number of aisles and tiers for the system and the velocities of the lift and shuttles are key parameters of analytical model which are assumed tobe given. The configuration of CTS is illustrated in Figure 4.
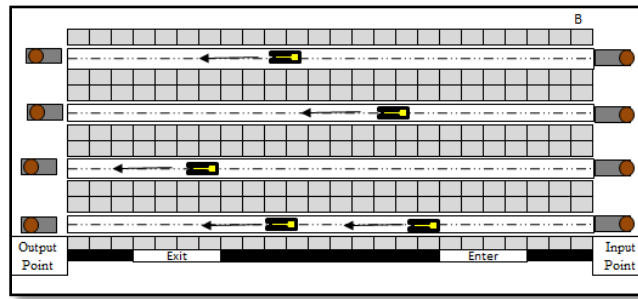
Fig. 4: The components of CTS configuration

With CTS, the single command cycle time calculation depends upon vertical, horizontal and depth movements. The formulation is provided below. The notations and equation are provided as follows:

$$H = T \times y \tag{5}$$

$$L = B \times x \tag{6}$$

$$D = A(2W + z) \tag{7}$$

$$E(SC) = \frac{E(L)}{v_x} + \frac{E(H)}{v_y} + \frac{E(D)}{v_x} + \delta \tag{8}$$

Where;

T	:	Number of tiers
B	:	Number of bays
A	:	Number of aisles
W	:	The width per aisle
H	:	Height of the rack
L	:	Length of the rack
D	:	Width of the aisle
x	:	The width of one storage rack
y	:	The height of one storage rack
Z	:	The depth of one storage rack
v_x	:	Horizontal velocity of shuttle
v_y	:	Vertical velocity of lift
$E(L)$	:	Expected vertical vehicle travel time
$E(H)$	:	Expected horizontal vehicle travel time
$E(D)$	:	Expected transverse vehicle travel time
$E(SC)$	:	Expected single-command round-trip travel time
δ	:	Load transfer time between vehicles and storage position

IV. EXCEL SPREADSHEET APPLICATION FOR COMPARISON

The purpose of the spreadsheet application is to calculate cycle time and it was first introduced by Eldemir et al., (2003) for only an AS/RS. The Excel spreadsheet study is enhanced within the scope of this study with the additions of cycle time calculations for both an AVS/RS and a CTS. The benefit of using a spreadsheet application will be demonstrated through an example calculation for a theoretical system. The

dimension of a particular load is supposed to be 5ft×5ft×5ft. The velocity of a crane, vehicle or shuttle differs from one warehouse system to another for both the horizontal and vertical movement. Cycle time is calculated based on a randomized storage policy and uses only single command transactions. For the cycle time computation in the spreadsheet tool, Visual Basic macro codes are embedded in the spreadsheet.

V. SCENARIOS

a) Essential Scenario

To understand which type warehouse system is more appropriate for a company, an essential scenario is set up with specific decision parameters: 1) Operational parameters which are concerned with warehouse strategies and deal with the number of items to be stored and the product range. 2) Design parameters consist of items related to the exact storage configuration including the number of aisles, bays, and tiers. This study takes into account only operational parameters by creating different scenarios. In the first place, the essential scenario is established by holding both operational and design parameters fixed and the basic specifications of the storage as shown in Figure 5. The number of aisles, tiers and bays are assumed to be 4, 5, and 50, respectively; and the width, length and depth of one storage rack are assumed to be 5ft each. Thus, the entire storage rack dimensions are 20ft×25ft×250ft.
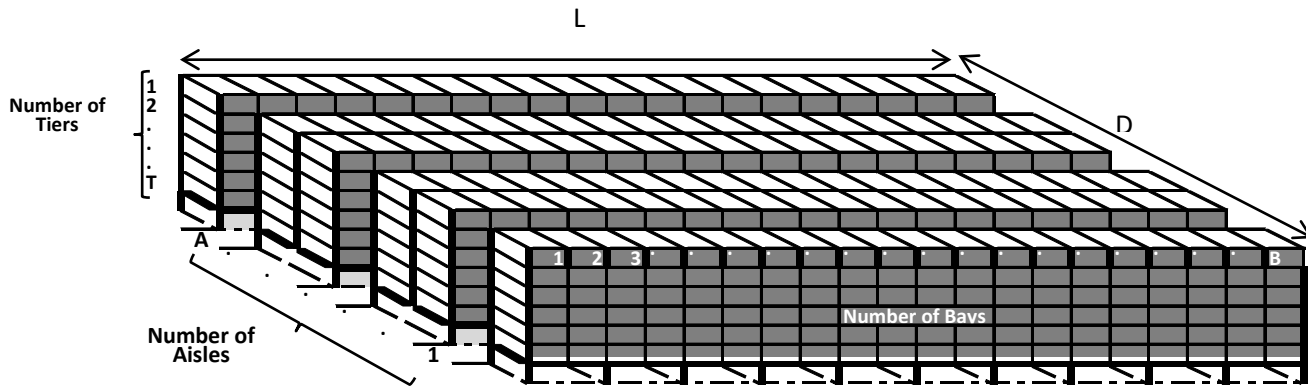
Fig. 5: Storage configuration

It is assumed that 1000 different items are available for this example and each one has its own particular space requirement. The space requirement values can show an alteration according to a uniform distribution, normal distribution, or a constant value defined by the user within the Excel spreadsheet. For the purposes of this study, the space requirement value is uniformly distributed with a minimum value of 1 and a maximum value of 18. The rate of retrieval and storage transactions is the same, and the transaction range is from 4 to 20 per day based on a uniform distribution. All values for the essential scenario are given below in Table 1 and are constant for three alternative warehouse systems.

Table 1: Parameters for the excel spreadsheet application

Prm	Description	Value
S	Number of Different Items	1000
A	Number of aisles	4
T	Number of tiers	5
B	Number of bays (columns) per aisle	50
D	Storage rack depth based on # aisles	20 ft
H	Storage rack height based on # tiers	25 ft
L	Storage rack width based on # bays	250 ft
x	Width of one storage rack	5 ft
z	Depth of one storage rack	5 ft
y	Height of one rack	5 ft

V	Number of vehicles	20
L	Number of lifts	4
λs	Arrival rate of storage transactions	U(4, 20)
λr	Arrival rate of retrieval transactions	U(4, 20)
λsr	Space Requirement Distribution	U(1, 18)
TL/U	Time to load/unload to	3 sec.
TT	Time between the lift and the I/O point	3 sec.

In the spreadsheet application, the total space requirement is based on a random storage principle as estimated by using a Monte Carlo sampling procedure. 10^4 samples are generated for this scenario and each sample is acquired by taking the total number of occupied storage spaces at any given time. After the samples are sorted in increasing order, the sample which has the maximum value is determined as the total space requirement. (Eldemir, 2003). According to the total space requirement, cycle time is calculated for each warehouse systems. The following Table 2 shows that CTS gives the smallest cycle time within the context of essential scenario assumptions if it is compared with other warehouse systems.

Table 2: Parameters for the excel spreadsheet application

Warehouse Systems	Cycle Time (in seconds)
AS/RS	130.615
AVS/RS	175.048
CTS	123.857

b) Change Scenarios for Operational Parameters

To reflect the real case analysis, three alternative warehouse designs are generated and used which vary in terms of company size: small, medium-sized and large company. These three company models are obtained by altering storage configuration and storage/retrieval transaction rates. The number of aisles and the number of tiers are determined during the scenario generation process; however, the number of bays utilized is derived based on the parameters seen in Table 3.

Table 3: Parameters for the excel spreadsheet application

| Prm	Description	S	M	L
A	Number of aisles	4	6	8
T	Number of tiers	3	5	7
λs	Arrival rate of storage transactions	U(0, 10)	U(5, 20)	U(10, 30)
λr	Arrival rate of retrieval transactions	U(0, 10)	U(5, 20)	U(10, 30)
D	Storage rack depth	20 ft	30 ft	40ft
H	Storage rack height	15ft	25ft	35ft
L	Storage rack width	200 ft	250ft	300ft

The Excel spreadsheet gives opportunities to evaluate the performance of the three warehouse systems using different scenarios. In this paper, two change scenarios are generated: 1) different combinations of space requirements for each item and 2) an increase in the diversity of items. These two scenarios are explained with their properties and results in detail as follows.

### c) Scenario 1: Different Combination of Space Requirement

The motivation behind the first scenario is to understand whether or not any difference in cycle time is seen between CTS and other warehouse systems for three facility size options when the space requirement is increased or decreased. In this regard, four different space requirement levels are specified according to uniform distribution: U (1, 5), U (1, 10), U (1, 15) and U (1, 20).
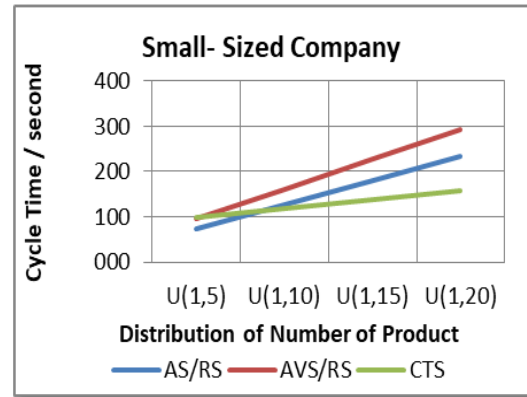

a)
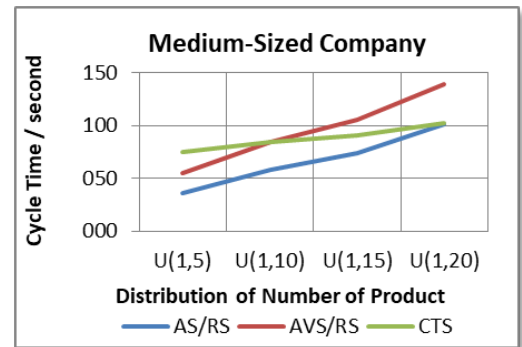
b)
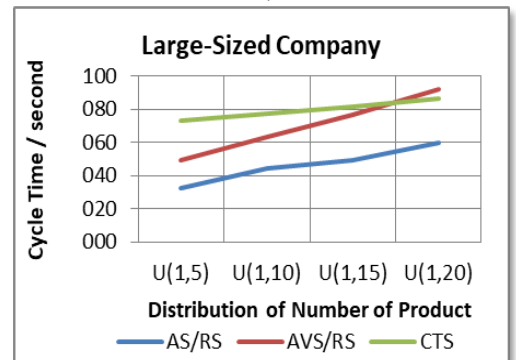
c)

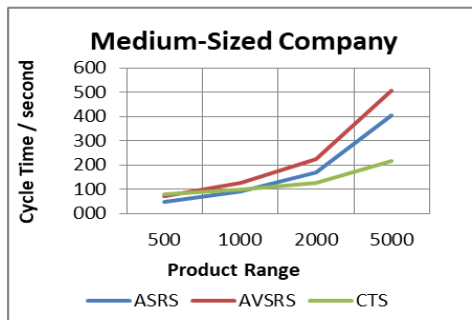*Fig. 6:* a), b) and c) Cycle time comparison with regard to company size

Figure 6 provides the cycle time results of three warehouse systems in response to different product size combinations for the three company types obtained from the Excel spreadsheet. What is interesting in this result is that cycle time is increasing for all-sized companies. However, it is assumed that the cycle time should decrease gradually when the amount of a given product is increased. The reason behind this assumption is the high probability of finding the required item easily because of higher availability rate of items in the warehouse. One of the causes for the cycle time to increase is due to the increased space requirement combined with a random storage policy.

Also, realizing an increasing trend in all graphs of three company sizes proves the greater degree of accuracy on this result. Another important finding is that, although the CTS provided the smallest cycle time for the essential scenario in previous study, it is not an appropriate warehouse solution for medium and large sized companies. This is due to the fact that the number of aisles falls the total cycle time significantly.
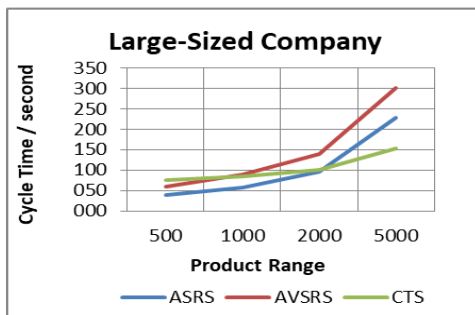
d)   *Scenario 2: Increase the diversity of items*
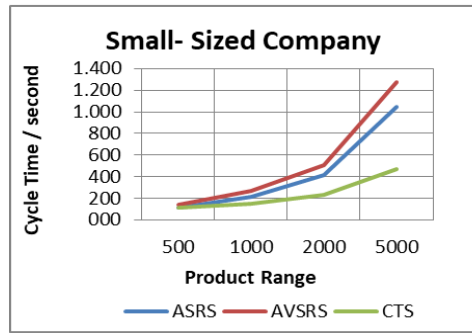
a)

b)

c)

Fig. 7: a), b) and c) Cycle time comparison for different product range

In the second scenario, the variety of products are increased and four different product ranges are generated as 500, 1000, 2000, 5000. The three graphs in Fig.7 show that there has been a sharp rise in the cycle time when the product range is increased from 500 to 5000 incrementally. Therefore, when any large or medium sized company does not have a diversified

amount of product, the AS/RS fits well as a warehouse system.

Besides, the horizontal and vertical velocities are different for all kind of warehouse systems. For instance, the crane within the AS/RS storage rack moves 5 feet/second whereas, the shuttle for an AVS/RS moves 4.16 feet/ horizontally. On the other hand, the multi-shuttles in the CTS travel inside the storage rack 6.56 feet per second and outside the storage with the velocity of 3.28 feet/ second. The speed for vertical movement is same for all three warehouse systems with 1 foot/ second. Therefore, the CTS gives the smallest cycle time results for a great variety of product range.

In CTS, each aisle has two lifts which are responsible for only either going up or going down separately. This decreases the waiting time in front of the lifts. In CTS, the shuttles are able to exit from the storage area in other words there is a flow available from the enter point of storage to the exit point. Thus, it increases not only the number of storage or retrieval transactions but also the shuttles do not need to come back to input/ output point again.

VI.   Summary And Conclusion

This study, firstly, was designed to introduce the alternative warehouse system, CTS, and compare it with other two well-known storage and retrieval systems, AS/RS and AVS/RS, using an analytic method. In order to reflect the characteristic of real world situations, three company sizes are generated. The comparison between CTS, AS/RS and AVS/RS is enhanced by taking account of these diversified company structures. Also, scenario planning method is utilized to demonstrate which warehouse system should be chosen in response to different product amount and different product range.

The most obvious finding to emerge from this paper is that each warehouse system is appropriate for only certain scenarios and some storage configurations. In other words, neither of warehouse systems could be suggested to provide the reasonable cycle time for all company sizes and all storage structures. This study raises a number of questions for future research. Further work needs to be done by using throughput rate parameters in addition to cycle time. Also, it is recommended that further research be undertaken to measure the effect of the number of aisle, bays and tiers individually.

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