Proceedings of the 2019 Winter Simulation Conference
N. Mustafee, K.-H.G. Bae, S. Lazarova-Molnar, M. Rabe, C. Szabo, P. Haas, and Y.-J. Son, eds.

SIMULATION-BASED PERFORMANCE EVALUATION OF A MANUFACTURING FACILITY WITH VERTICAL AS/RS

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ABSTRACT

Klein Mechanisch Werkplaats Eindhoven (KMWE) is a precision manufacturing company situated in the Netherlands and recently relocated to a new location known as the 'Brainport Industries Campus' (BIC). This move allowed KMWE to improve the performance of its manufacturing facility known as the 'Tool Service Center' (TSC) by investing in vertical automated storage and retrieval systems (AS/RSs). However, these decisions needed to be made under input uncertainties since the move to BIC and modernization of existing equipment would cause changes in operating parameters inside the facility, over which little information was known in advance. In this study, we show how hybrid simulation modelling was used to assess the impact of input uncertainties (such as operator productivity, vertical storage height) on the throughput performance of TSC. Ultimately, the outcomes of this research project were used by KMWE to make an investment decision on new equipment acquisition quantity.

1 INTRODUCTION

Klein Mechanisch Werkplaats Eindhoven (KMWE) is a contract manufacturer in the Netherlands specialized in high precision machining. Their product portfolio consists of complex products (e.g., an average of 40 tools needed for manufacturing) ordered in low volume (e.g., batch sizes up to 20 units, order frequency less than four times per year). The combination of these two characteristics yields several operational challenges which revolve around tool management. Timely availability of tools is an essential parameter for the seamless performance of the production shop floor. The availability of tools is primarily determined by the performance of the 'Tool Service Center' (TSC). This department is responsible for the assembly, validation, and release of tools to the shop floor. Because of the high number of change-overs, the TSC has to pick, assemble, and measure up to 250 tool assemblies per day. The current design of the TSC is capable of keeping up with these system requirements. However, the expected growth of KMWE in product portfolio causes KMWE to reconsider their current layout, processes, and equipment of the TSC. It is expected that this department has to deliver up to 400 tool assemblies per day within a few years. Alongside the expected growth, KMWE is currently (April 2019) moving to the Brainport Industries Campus (BIC). This campus is meant to be a leading hub where innovation and competitiveness in high-tech manufacturing reach the highest level of excellence. It is to become a place where suppliers, educational institutions, and specialized companies come together, combine their strengths, and achieve operational excellence (BIC 2019).

The move to the BIC created an opportunity to invest in new equipment, improve shop floor layout, and change business processes. The possible equipment upgrades consisted of either investing in one or two vertical AS/RSs. Replacing the current horizontal storage cabinets with new equipment would render the saved space for other value-added operations. Moreover, equipment with higher throughput performance would support the future growth objectives of the company.

In this production setting, equipment investment decisions were challenging in practice owing to several factors: First, uncertainties regarding the new storage unit had to be considered. For example, the impact of new AS/RSs on facility throughput due to variation in operator's picking performance (i.e., expected picking time of tools from the vertical AS/RS) needed to be evaluated. However, the operator picking speeds at the new storage units were unknown. Typically, storage units are equipped with picking support systems by means of a laser assistance technology, that is, a pick-to-light system indicates the quantity and the item to be picked. In our specific production setting, it was difficult to distillate any cycle times from the information provided by the supplier. Also, when the facility has two vertical AS/RSs, the picking process should involve an operator serving two vertical AS/RSs in parallel. In such cases, the operator productivity increases because while the first unit retrieves the next level, the operator can pick tools from the other vertical AS/RS unit. The picking support might cause operators to finish picking from the first unit while the level on the second unit is still being retrieved. In addition, how throughput would change as a result of the number of levels within the vertical AS/RS was unknown. The vertical storage/retrieval unit has a fixed width and length but the height of the vertical AS/RS unit is adjustable based on the number of levels stacked within it. This implies that if the number of levels increases, the overall height of the vertical AS/RS would also increase, and subsequently result in longer retrieval times. Furthermore, operator walking speed and the distribution of picking time introduced additional layers of uncertainty to the model.

Thus, the key research objective of this study was to estimate the throughput performance of the TSC under the input uncertainties mentioned above and to aid the investment decisions regarding new vertical AS/RSs. We developed a hybrid simulation model to evaluate the system performance under different AS/RS configurations. Agent-based modelling was used to capture the dynamics of a vertical lift module and its interaction with the operator while discrete-event modelling was used to model the processes inside the TSC. Simulation experiments showed that using two vertical AS/RSs in this specific production process would lead to a robust system design against fluctuations in picking times, and would support the objective of dispensing up to 400 tool assemblies per day from this facility. The outcomes of this research project have been implemented in practice by KMWE, leading to the acquisition of two vertical AS/RSs.

Performance analysis of an AS/RS is a complex problem, and simulation has been conventionally used to evaluate facility requirements (Eneyo and Pannirselvam 1998). Some approaches exist for performing such an investigation (Pulat and Pulat 1988). There exist reports on applications of simulation to model an AS/RS and key performance indicators (Gunal et al. 1993; Gaku and Takakuwa 2017). Usually, the AS/RS is modeled precisely and realistically to behave as the real system does (Takakuwa 1995). The model in this paper employs *parts-to-picker system* which presents a high risk of creating bottlenecks in the picking bay due to the storage assignment. However, this solution reduces the percentage of labour time and increases the retrieval productivity. There is a trade-off between walking to collect tools in a horizontal setting and waiting for the lift mechanism to present the required level. The issues related to AS/RS systems are detailed in (Roodbergen and Vis 2009). Further, Meller and Klote (2004) developed analytical models to determine the throughput of vertical lift modules (VLMs). In this study, we consider the throughput performance of vertical AS/RSs under input uncertainty on several parameters, such as, picking times (i.e., mean and distributions), number of levels in vertical AS/RSs, and operator walking speeds. We conclude that automation can have an unanticipated impact on the overall performance if equipment portfolio selection is not scrutinized with regard to the changes it brings to the operating parameters inside the facility.

The remainder of this paper is organized as follows: In Section 2, we present the facility under study and elaborate on the current and modified processes. We present the simulation model in Section 3. In

Section 4, we analyze the output results from the simulation model. Finally, we present our conclusion and future research directions in Section 5.

2 SYSTEM DESCRIPTION

The design, working procedure, and equipment of the TSC have to be designed in such a way that the short deadlines are met. For completion, several sequential/parallel activities have to be taken care of. This section will elaborate on the process at the TSC.

2.1 Work Order

As mentioned in Section 1, the TSC is established to supply the necessary tools to the shop-floor. The demand for these tools is communicated to the TSC by a work-order (order containing a list of tool assemblies required to carry out production). This work-order triggers the activities that take place at the TSC. Unfortunately, these work-orders are not known in advance and have a short deadline. Usually, work-orders have to be completed within one working day.

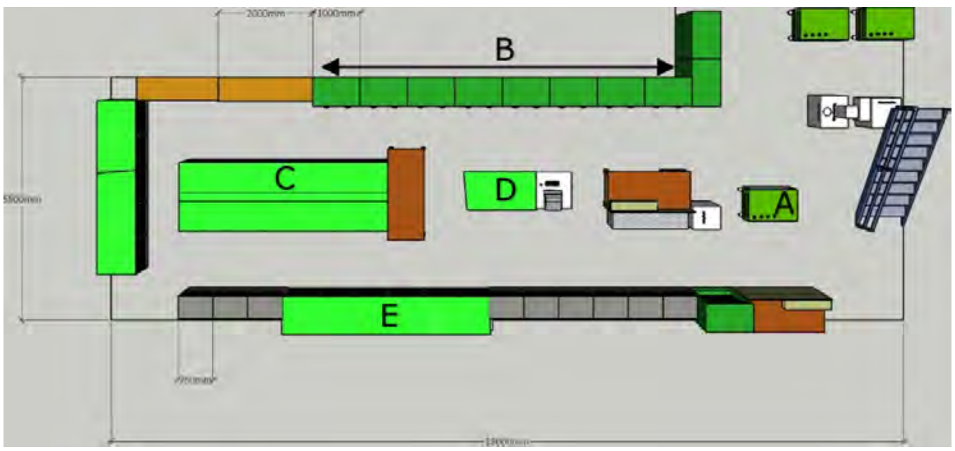


Figure 1: Layout of the Tool Service Center (TSC).

Each work-order consists of one or more tool assemblies. The components (individual tools) of each tool assembly have to be picked separately, assembled, and measured as a whole. All tool assemblies within a work-order have to be measured apart. Therefore the three main activities for the TSC are picking, assembly, and measurement. These three activities are processed at a dedicated place within the TSC and the required equipment is not movable. The location of each process is fixed and influences the lead time of work-orders. The significance of the location of various stations, and subsequently the importance of finding their optimal locations, had to be investigated before the move to the BIC. The current layout of the TSC is straightforward and given in Figure 1. At point A, the work-orders which are generated on the shop floor are collected and prepared to be processed within the TSC. Point B shows the storage equipment where tools are picked. At point C, the tools are assembled and subsequently measured at Point D. Finally, point E indicates the location where all tool assemblies are collected for release to the shop-floor. The un-allocated work-order with the highest priority is assigned to the first idle operator. As soon as the work-order is collected the operator proceeds to the picking process.

2.2 Picking and Assembly

Two working procedures within the combined picking and assembly process are applied at KMWE. $Option-I$ signifies a process where the picking and assembly process are executed in parallel, that is, the required tools for a tool assembly are picked and put together immediately before moving to the next tool assembly. $Option-II$ signifies a process where the picking and assembly process are executed sequentially, that is, all tools are picked first and put together later. For this simulation study options I and II were incorporated for the current layout with horizontal storage and the layout with vertical AS/RS respectively. Moreover, $Option-II$ is most likely to be applied within the new situation at the BIC, and $Option-I$ is the existing operating sequence.

2.3 Measurement

Measurement is processed at a dedicated machine with a limited capacity of two work-orders. The software on the machine requires work-orders to be measured as a whole, which means that all tool assemblies have to be assembled and present before the first assembly can be measured. This constraint implies a straightforward process flow.

2.4 Storage Mechanisms

Currently, TSC contains a horizontal storage cabinet. The horizontal storage is an 8-meter long cabinet where components are stored on levels. There are 48 levels in the considered horizontal storage cabinet. These levels have fixed dimensions and are always approachable for the operators. No extra equipment (e.g. ladders, forklift trucks, etc.) is required in order to pick the components. Potential equipment to replace the horizontal storage is a vertical AS/RS also known as a vertical lift module (VLM). It is an automated storage and retrieval system where levels are retrieved and presented to the operator by a lift mechanism. Each vertical AS/RS contains an Input/Output (or I/O) location from where operators can operate the AS/RS system and pick components from the retrieved level. This implies that operators cannot work simultaneously on a cabinet and levels are not always approachable. Interested readers are referred to Richards (2017) for further review on VLM.

The specifications for the vertical AS/RS was obtained from the manufacturer's specification sheet. The width and height of the vertical AS/RS considered in this study are 2.5 meters and 2.8 meters, respectively. However, the height of the vertical storage is dependant on the number of levels that each AS/RS contains. The height of each level is also dependant on the height of the tool that it holds. Thus, the exact height of the vertical AS/RS cannot be determined since it is calculated cumulatively based on the height of the levels. Based on the minimum desired storage capacity of the vertical AS/RS, a minimum number of levels was estimated to be 60. The height of the Input/Output location is set to 1 meter.

2.5 Picking Process

The picking procedure from the horizontal rack follows a picker-to-goods definition. Operators have to walk alongside the cabinet and pick the components from the levels which are already presented to the operator. This system enables operators to pick simultaneously from the levels. However, the horizontal storage requires more floor space, space which can be used for more productive tasks. The picking procedure of the vertical AS/RS characterizes itself as a goods-to-picker concept. An operator submits the request for a level at the Input/Output location and the AS/RS system retrieves the desired level. This implies that only one level can be serviced at once and parallel work of operators is made impossible. After the level has been presented to the operator, a picking support system indicates the location of the component that has to be picked. These small improvements immediately enhance employee productivity.

At the time of the project implementation, picking times from the vertical AS/RS were uncertain. In the picking process, the source of uncertainty arises due to the interaction of operators with the vertical AS/RS. In fact, one of the main goals of this study was to justify the equipment acquisition decision under input uncertainty regarding picking times. The input models for the picking times were based on interviews with process experts and original equipment manufacturers. We decided that uniform and triangular distributions were appropriate input models for sampling an input variable for the picking process.

Due to the lack of knowledge on appropriate parameters of these distributions, it was decided to vary their parameters and compute facility throughput values. The dynamics of the picking process would have a direct impact on the acquisition decision of the vertical AS/RS systems.

The sequence of events in the picking process is illustrated in Figure 2. V1 represents the time-line of the picking process from a layout which contains one vertical AS/RS. As observed, the sequence of tasks is sequential with possible waiting between successive tool picks. $V2_a$ and $V2_b$ represent picking process from a layout that contains two vertical AS/RSs, where a and b represent the individual vertical AS/RS machines. This process enables the operator to carry out tool picks in parallel, that is, the operator picks from $V2_a$ while the lift of $V2_b$ retrieves the desired level from its resting position to the Input/Output location. In the time-line, processes marked with asterisk (**Process*) are carried out by human operators and the rest is carried out by the lift of the vertical AS/RS.

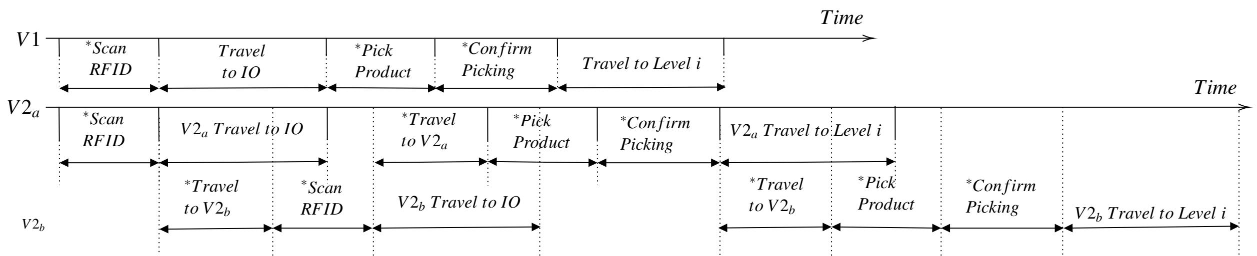


Figure 2: Timeline of the picking process at vertical AS/RS machine; $V1$ represents operation sequence when the facility consists of 1 vertical AS/RS; $V2_a$ and $V2_b$ represent operation sequence in the facility with 2 vertical AS/RS machines.

- Scan RFID : This event corresponds to the action of human operator scanning the RFID at a vertical AS/RS as a means to communicate the requirements of tools to be picked up. This process hardly takes any time and is almost instantaneous.
- ($V2_{a/b}$) Travel to IO : This event signifies the time taken by the lift of a vertical AS/RS to retrieve a component from its resting location to the Input/Output location.
- Pick Product : This event signifies the time taken by an operator to pick up the product(s) from the level at I/O location.
- Travel to $V2_{a/b}$: This event signifies the time taken by an operator to travel from I/O location of one vertical AS/RS to I/O location of the other vertical AS/RS.
- Confirm Picking : This is a signal sent by the operator to the vertical AS/RS once he/she has picked up required tools from the level at I/O location.
- Travel to Level i : After *Confirm Picking*, the lift puts the level back at original/resting position.

Machine operating parameters are fairly certain and known in advance. The source of uncertainty regarding the process of picking arises due to human operator's interaction with the vertical AS/RS. Events *Pick Product* and *Travel to* $V2_{a/b}$ is dependant on the human operator's working productivity and walking speed. While event *Travel to IO* is based on the number of levels in the vertical AS/RS machine. Further, the lift travel time of vertical AS/RS is dependant on the storage assignment policy. Since we follow a random assignment policy, the travel time is uncertain.

3 SIMULATION METHODOLOGY

3.1 Data Collection and Model Assumptions

The data collected as part of this study comprised *interviews with process owners*, *production data* and *commercially available data* for potential investments. The data consist of the following items.

- Arrival of Work-orders: It is assumed that there are always work-orders for operators to process since the focus is on calculating the throughput capacity of the system. The number of tool assemblies in a work-order is variable and can be defined by the user. In this research, however, we assume a work-order with a fixed number of tool assemblies and a fixed number of tools.
- Service Times: These consist of manufacturing operations such as assembly and measurement as defined in Section 2. These were modeled as triangular distributions after discussing with process owners, more specifically, we used triangular $(1.5,2,2.5)\times N$ minutes and triangular$(0.5,1,1.5)\times N$ minutes for assembly and measurement, respectively, where N is the number of tool assemblies in a work-order.
- Location of tools in racks: In horizontal storage, tools are placed randomly. This is representative of the actual situation where there is no specific storage policy for placing tools in levels of a rack, and hence, tools are placed randomly based on available storage space. The operators, based on their experience, know where the components are kept and pick them when required. For horizontal storage, it was estimated that the operators require about 10 to 20 seconds to pick a tool from a level and it was modeled as a Uniform distribution (Uniform(10,20) seconds per tool pick). In vertical storage systems, we assume the same random placement of tools in the levels. The picking time for tools from a vertical storage is expected to be much shorter than the horizontal storage since the vertical storage system is equipped with a laser that points to the location of the tool to be picked up, thus, saving time normally spent on searching tools in a horizontal layout.
- Height of the levels: Height of a level depends on the maximum height of the tool that it holds (for example, if the maximum height of a tool is 85mm among other tools, then level height is set to 85mm). Based on expert opinion, we set each level height to be uniformly distributed between 70 and 100 millimeters.
- Layout: Schematic diagrams were made available of the layout. The simulation model was made over these schematics to capture the dynamics of this workshop as close to reality as possible.
- The TSC is simulated with 4 operators working without breaks. Each simulation day can be regarded as 3 actual work shifts of 8 hours each.

In addition, certain model assumptions were made which are listed below:

- Operators are assumed to be equally productive, however, we scale operator walking speed with the help of scaling coefficient later in this study.
- Tools have a unique location in horizontal and vertical storage systems (however, it may vary depending on simulation iteration).

3.2 Main Elements of the Simulation Model

The simulation model is built on the multi-method simulation software – AnyLogic University v8.3.1 (AnyLogic 2019). It supports the three major methodologies that are used to build dynamic business simulation models – discrete event modeling (DES), agent-based modeling (ABM), and system dynamics (SD). Here, a combination of agent-based modeling and discrete event simulation was used to model the dynamics of the vertical AS/RS and the operation sequence inside the TSC respectively. In practice, we closely followed the methodology defined by Sturrock (2015).

The model consists of one entity, the work-order, which goes through the process blocks, seizes resources (operators), and governs the order picking sequence (Section 2.2). The main process flow is represented in Figure 3 along with the choice of picking strategies. Picking strategy is dependant on the type of layout. The current process with horizontal storage uses $Option-I$. Layouts with vertical AS/RS use $Option-II$.

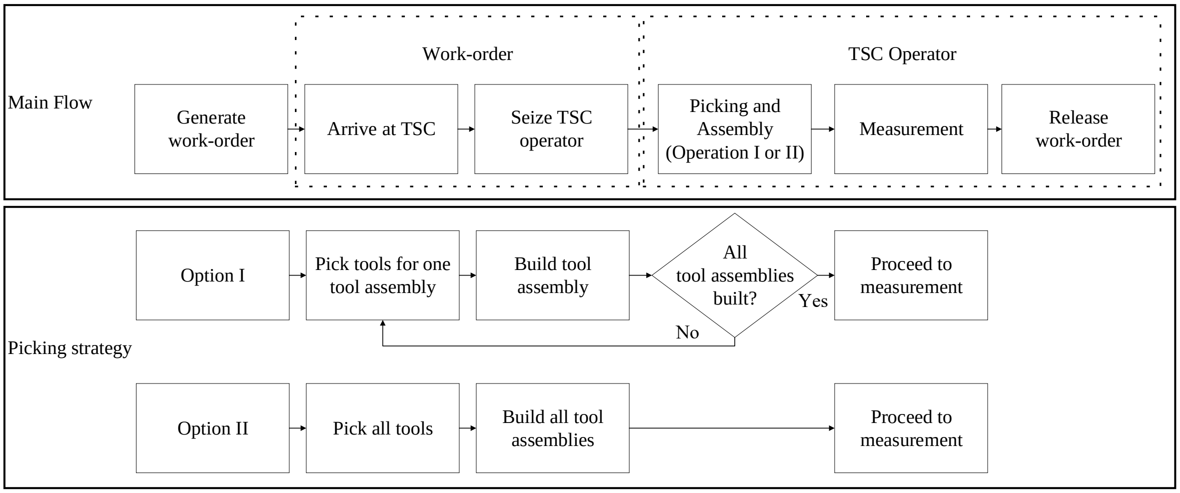


Figure 3: Process flow diagram of TSC highlighting the main flow of the simulation model and the choice of picking strategies.

3.3 Configurations

This section defines the various configurations of TSC considered in this study. We define scenarios for the layout with horizontal racks and for the layouts with vertical AS/RS system, visualized in Figure 4.

- Horizontal : This scenario represents the layout consisting of horizontal storage mechanism currently in use. The facility contains a horizontal storage 8 meters in length with 48 levels holding tools.
- Vertical 1 : In this scenario, the facility is assumed to contain a single vertical AS/RS with L levels stacked on top of each other holding tools.
- Vertical 2 : In this scenario, the facility is assumed to contain two vertical AS/RS in parallel, with L levels stacked on top of each other holding tools.

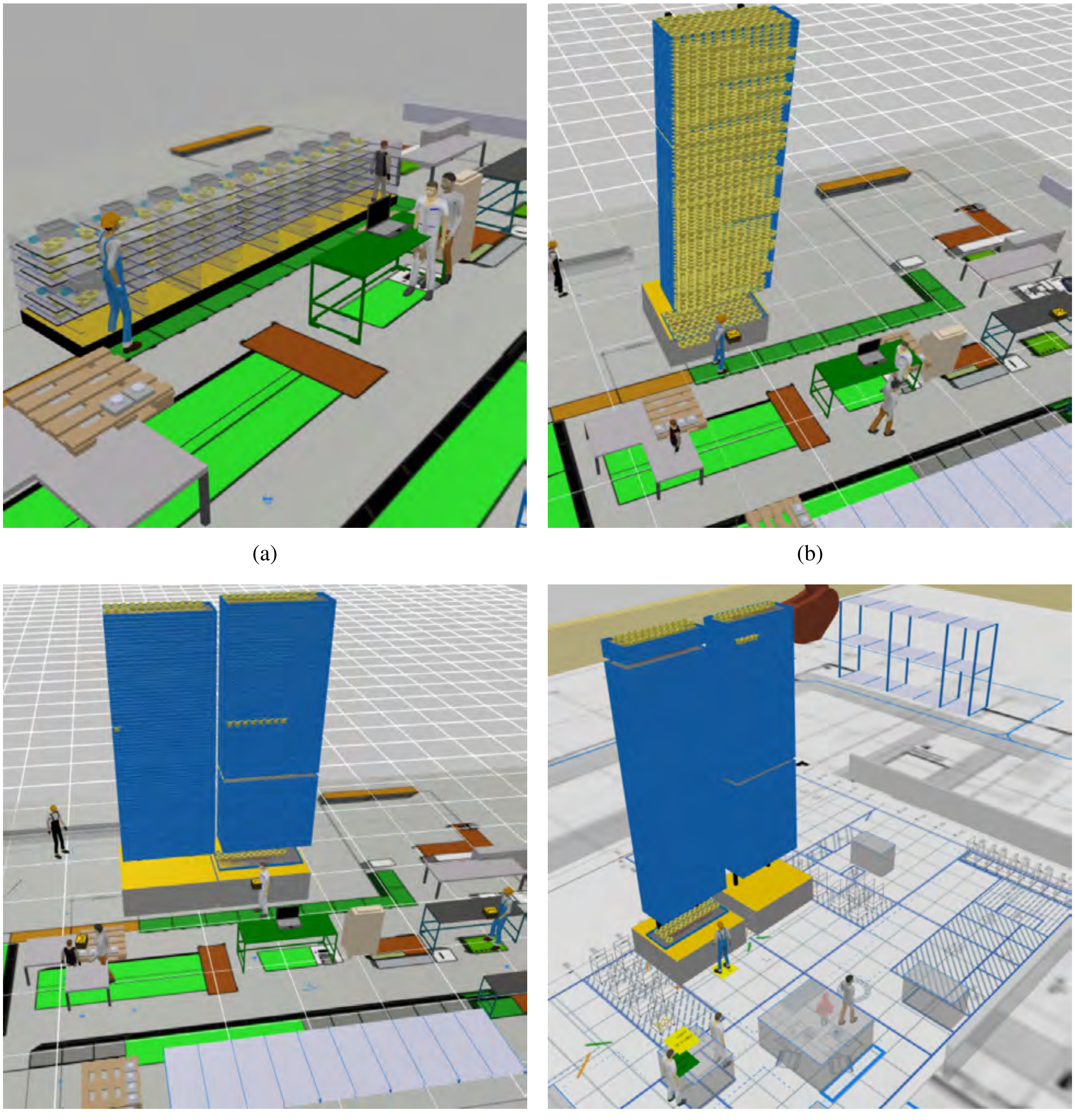
4 EXPERIMENTATION

4.1 Numerical Analysis Setup

We set up numerical experiments to investigate the impact of the parameters: Picking time (P), Operator Speed (W_s), and number of Levels (L). We combine the following scenarios – 6 Picking time scenarios P1-P6, 3 Scenarios of number of levels in the vertical AS/RS L1-L3, 5 scenarios for the worker speed W1-W5. Here, we use scaling coefficient $K \in \{0.6, 0.8, 1.0, 1.2, 1.4\}$ for a constant worker speed of W = 0.8m/s. These scenarios are summarized in Table 1.

Picking time comprises of *Scan RFID*, *Pick Product*, and *Confirm Picking Events*, as introduced in Section 2.5. We categorize picking times into optimistic, realistic, and pessimistic regions to represent the variation in picking times. It is important to specify that the picking models are known for horizontal storage systems and act as benchmarks for performance evaluations. The performance evaluation of the facility with horizontal storage uses a picking time distribution of Uniform(10,20) seconds. Note that, from now on, the picking time is denoted by its mean i.e., for Uniform distribution, $\mathbb{E}[P] = \frac{1}{2}(min + max)$ whereas for triangular, it is $\mathbb{E}[P] = \frac{1}{3}(min + max + mode)$ where min, max, and $mode$ are minimum, maximum, and mode values of the distribution.

Once the method of sampling input parameter values were determined, we set up a Monte Carlo experiment. Monte Carlo experiment obtains and displays a collection of simulation outputs for a stochastic model or for a model with stochastically varied parameter(s).The experiment allows us to run simulation a



(a) (b) (c) (d)

Figure 4: Simulation model scenarios. (a) Horizontal, (b) Vertical 1, (c) Vertical 2, (d) Vertical 2 in new layout.

Table 1: Scenarios for uncertain inputs; $\mathbb{E}[P]$ – expected picking time, in seconds.

Picking Time (P), seconds				Number of Levels in vertical AS/RS (L)		Operator Walking Speed(W_s) , meters per second, W = 0.8 m /s		
		P	$\mathbb{E}[P]$		L		K	W_s
Optimistic Region	P1	Uniform(3,6)	4.5	L1	60	W1	0.6	$W \times 0.6$
	P2	Triangular(3,6,4.5)	4.5	L2	80	W2	0.8	$W \times 0.8$
Realistic Region	P3	Uniform(5,10)	7.5	L3	100	W3	1	$W \times 1.0$
	P4	Triangular(5,10,7.5)	7.5			W4	1.2	$W \times 1.2$
Pessimistic Region	P5	Uniform(10,15)	12.5			W5	1.4	$W \times 1.4$
	P6	Triangular(10,15,12.5)	12.5					

number of times, obtain the collection of outputs, and view them as a histogram. The simulation experiment is a combination of known input models (arrival pattern, service times, number of workers, etc.) and models representing input uncertainty. We rely on such a methodology since it quantifies the reliance of facility performance on uncertain input parameters and assists in making acquisition decisions regarding the vertical AS/RS. The total simulation model time is set to 28800 minutes (20 days) for 10 replications to find the 95% confidence intervals. We investigated all combinations of (P1-P6), (L1-L3), and (W1-W5) in all 90 combinations, and in each of these combinations, we calculate the following performance indicators: (i) Hourly throughput rate (Number of Tool Assemblies processed per hour) of Assembly, Measurement, and the Facility, and (ii) Picking Rate (Number of Tools retrieved from vertical AS/RS per hour).

4.2 Output Analysis

Figure 5 shows the expected facility throughput based on walking speed of operators (represented by scaling coefficient K) and Expected Picking Time ($\mathbb{E}[P]$) for number of levels L = 80. We observe a decrease in facility throughput with an increase in expected picking time of tools from Levels. In scenarios considering optimistic picking time ($\mathbb{E}[P] = 4.5$ seconds), there is a shift in facility throughput performance between Vertical-1 and Horizontal, that is, when expected picking time is 4.5 seconds and operators walk at lower speeds, the performance of Vertical-1 configuration is better than Horizontal configuration. However, with increase in operators' walking speeds, the performance of Vertical-1 configuration degrades and eventually falls below the horizontal configuration. Vertical-2 remained the best in this region.

In scenarios considering realistic picking time ($\mathbb{E}[P] = 7.5$ seconds), the performance of Vertical-2 configuration was higher when compared to Horizontal. However, the performance of Vertical-2 seemed to be converging with Horizontal with increase in operators' walking speeds. In region of pessimistic picking time ($\mathbb{E}[P] = 12.5$ seconds), there was a shift in performance from Vertical-2 to Horizontal. Vertical-1 performed the worst in this region. We observe a similar trend when number of levels is 60 and 100.

Vertical-1, thus, under-performs in most of the considered scenarios except when the operators' walking speeds are relatively low. Vertical-2 outperforms Horizontal in most of the scenarios except when the tool picking time increases (pessimistic picking time region). This result shows that picking time can have a high impact on relative performance of different configurations.

Figure 6 shows the variation in mean picking rate in relation to change in number of levels (L) in a vertical AS/RS and Operator Walking Speed (represented by scaling coefficient K) under a constant expected picking time $\mathbb{E}[P] = 7.5$ seconds. The picking rate reflects the ability of the vertical AS/RS to dispense tools under constant demand. Vertical-2 remained insensitive to the increase in number of levels

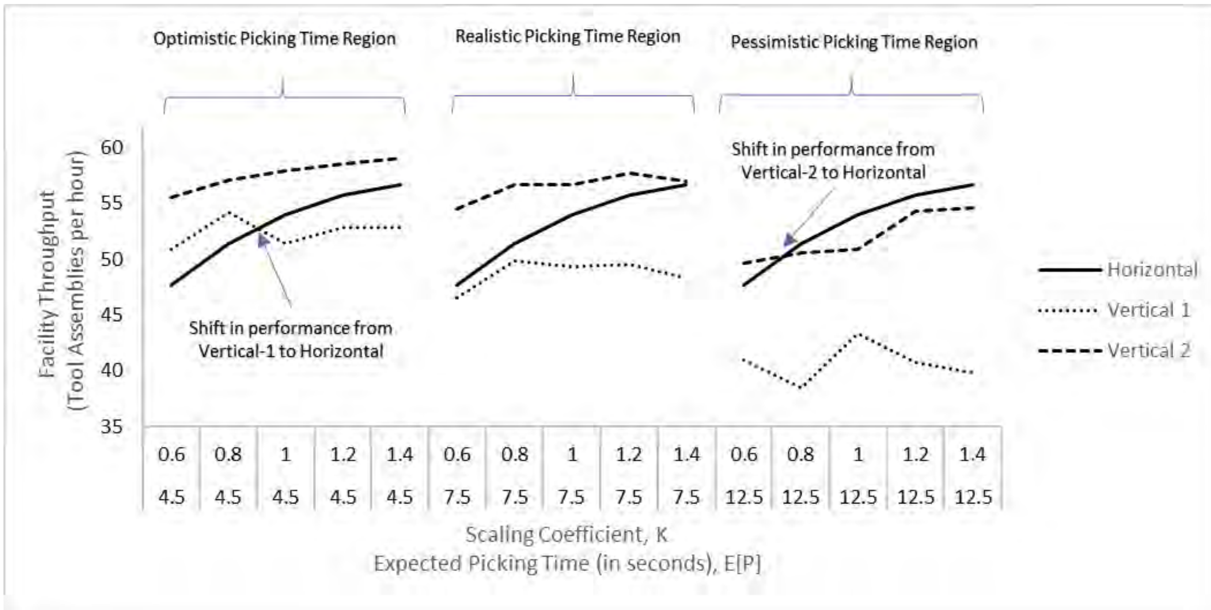


Figure 5: Mean facility throughput; number of levels, L = 80.

inside vertical AS/RS machines while Vertical-1 showed a downward trend with an increase in number of levels. The downward slope signifies the degradation in the capability of Vertical-1 configuration to dispense tools with an increase in the number of levels. This degradation may eventually lead to picking process at vertical AS/RS acting as a bottleneck under heavy demand. Vertical-2 proved to be robust to changes in number of levels under realistic picking times.

On further analysis, it was observed that the average waiting time between two consecutive tool picks increased with an increase in number of levels in Vertical-1 configuration. Waiting time between successive picks in Vertical-2 remained insensitive to a change in height due to operators alternating between two vertical AS/RS machines to carry out the same task on separate machines.

To conclude, numerical experiments indicate that Vertical-2 could be a good configuration for KMWE under uncertainty in picking times and number of levels. It proved to be robust against changes in the number of levels and enabled fast picking rates to realize the stipulated objective of dispensing 400 tool assemblies per shift, under realistic picking time assumption. Moreover, it provides enhanced storage capabilities and shows improvement over current configuration in terms of throughput performance. In Table 2, we highlight some values from numerical analysis along with 95% confidence intervals. It was observed that the choice of probability distribution had little impact on the output parameters.

Next, we discuss the financial implications of these design configuration. KMWE associates an hourly cost (5 euros per hour per m^2) to a unit square-meter area in its facilities, that is, having more area available for production equates to better utilization of available floor space. Horizontal storage covered 24 m^2 (8 Racks $*$ 3m $*$ 1m) floor area while Vertical-1 occupies 7 m^2 (2.5m $*$ 2.8 m) and Vertical-2 occupies 14 m^2 (2 Racks $*$ 2.5 m $*$ 2.8m) floor area. The total monthly cost savings in Vertical-1 configuration amounts to 20,400 euros per month and 12,000 euros per month in the case of Vertical-2 configuration. In terms of costs, Vertical-1 is the best, however, the performance benefits of having two vertical AS/RSs take precedence over the reduction in cost due to reducing floor space. A more productive (e.g. more tool assemblies per day) TSC enables productivity increase on the shop floor as well. Subsequently, this supports KMWE in its ambition to grow in turnover.

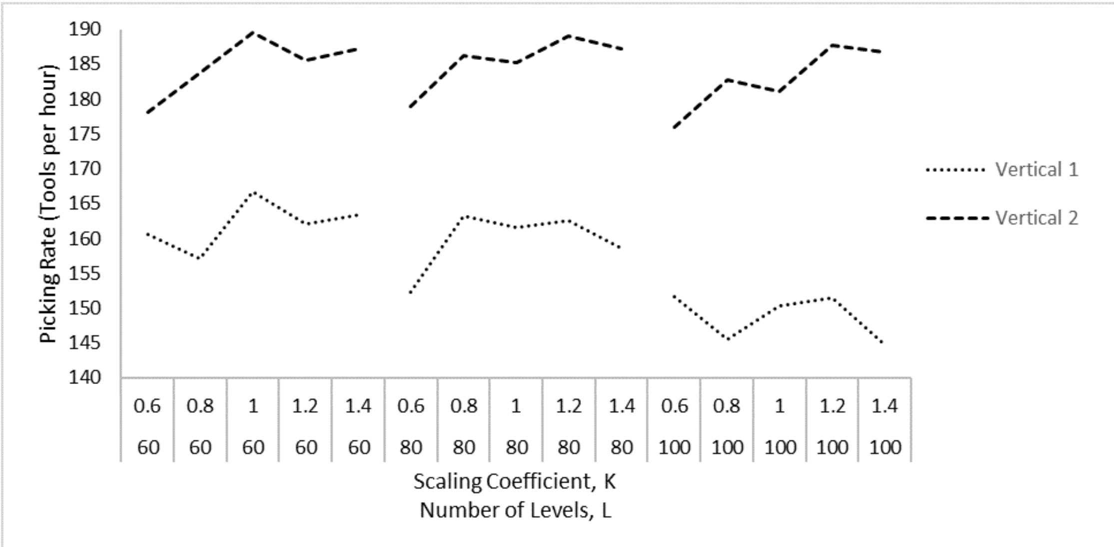


Figure 6: Mean picking rate from vertical AS/RS; expected picking time, $\mathbb{E}[P] = 7.5$ seconds.

Table 2: Table showing selected hourly throughput rate (number of tool assemblies processed per hour) of assembly, measurement, and the facility out of the 90 evaluated scenarios, L = number of levels, K = scaling coefficient for operator walking speed, W_s = operator walking Speed, P = picking time distribution in seconds, U = *uniform*, T = *triangular*. The results are displayed with 95% confidence interval.

				Vertical 1						**Vertical 2**					
				Assembly		Measurement		**Facility**		Assembly		Measurement		**Facility**	
L	**K**	**Ws**	**P**	Mean	CI	Mean	CI	**Mean**	**CI**	Mean	CI	Mean	CI	**Mean**	**CI**
60	1	0.8	U(5,10)	51.27	2.27	50.93	2.46	50.87	2.51	58.33	1.27	58.00	1.05	57.87	1.04
60	1	0.8	T(5,10,7.5)	50.13	0.51	49.87	0.44	49.80	0.51	58.27	1.61	57.73	1.72	57.60	1.61
80	1.4	1.12	U(3,6)	53.33	3.01	53.00	3.01	52.87	3.20	59.53	0.70	59.13	0.84	59.07	0.92
80	1	0.8	U(5,10,7.5)	49.73	2.85	49.40	2.85	49.33	2.78	57.00	1.78	56.80	1.89	56.73	1.87
80	1	0.8	T(5,10,7.5)	48.67	2.99	48.40	3.01	48.27	2.85	57.00	1.27	56.73	1.28	56.47	1.26
80	0.6	0.48	U(10,15)	41.40	2.40	41.07	2.38	41.00	2.22	50.00	2.06	49.67	2.06	49.67	2.06
100	1	0.8	U(5,10)	46.27	2.83	46.00	2.72	45.87	2.61	55.73	1.70	55.47	1.64	55.33	1.36
100	1	0.8	T(5,10,7.5)	46.20	3.43	45.87	3.43	45.80	3.36	56.80	1.97	56.27	1.98	56.27	1.98

5 CONCLUSION AND FUTURE RESEARCH

A hybrid simulation model (DES-ABM) was designed to analyze the throughput performance of the TSC with horizontal storage and vertical AS/RS functioning under uncertain input parameters. It was shown that Vertical-2 configuration had significant benefits over Vertical-1 and Horizontal configurations in terms of throughput performance and floor space requirements, respectively. The picking rate for Vertical-2 configuration, under the given model setting, was robust to changes in the number of levels. Thus, the model assisted KMWE managers in making an informed decision while selecting the equipment portfolio for future investments and highlighted the risks of underestimating the acquisition quantity of the proposed vertical AS/RS equipment. KMWE used the results of this study to invest in two vertical lift modules and installed them on the new layout at BIC.

As a next step, the proposed model was retrofitted to the new layout (Figure 4d) to provide a platform to carry out further research. The proposed model is now being used to incorporate worker shifts and examine different operating rules inside the TSC. Future studies could also analyze the effect of replacing random allocation rule with more sophisticated allocation rules for tools inside vertical AS/RSs.

ACKNOWLEDGEMENT

This research is a part of the Advanced Manufacturing Logistics program jointly funded by KMWE, IJssel Technologie, Rubix, TU/e, Erasmus, and Provincie Noord Brabant. We are grateful for their support.

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