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Pick capacity model for cutting machine tools stored in a next generation Vertical Storage Machine

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Abstract

Tools for a group of cutting machine tools in a workshop are often centrally stored, maintained and prepared for use. Using a vertical lift machine (VLM) allows orderly and space-saving storage. It is expected that the total time to prepare tools for delivery in the workshop depends on the chosen VLM architecture and on the strategy for organising the tools in the VLM.

This research proposes a mathematical model for determining the total preparation time as a function of the number of items ordered for a series of jobs in the workshop. The model is specific applied for machine cutting tools. While previous research focussed on storage strategies for carrousel storage machines or the basic VLM architecture, this research focusses on five VLM architectures that can be combined with three storage strategies in the mathematical model. The model is largely parametric, allowing for specific numerical values as applicable to the workshop being calculated and allowing to use the technical performance parameters of the VLM.

The model illustrates that both the choice of the designated VLM architecture and the choice of storage strategy can have a significant impact on the total time needed to prepare the tools. For both choices to be made, no general rule emerges: a calculation with the specific numerical values for the workshop concerned is appropriate.

Keywords: Vertical Lift Module, Pick Capacity, Machine Tools, Pick capacity Model

1. Introduction

Cutting machine tools for milling and turning machines in machining centers are supposed to be available when needed. The tools that will be needed are most often specific to the machining jobs that have been planned. The vast majority of tools that is going to be used is known at least a couple of hours on beforehand [1] and need to be loaded into a machine. Which product will be produced on which machine and with which tools is a problem called “Machine Loading Problem”, where profit is maximized over a given time for all the machines. [2] Solving the Machine loading problem, they assume that all the tools are available and ready to use. However, these tools need to be picked from their storage location and brought to the machine. The time needed to retrieve the required tools is not considered into the current solutions. [3]

Some production plants using such machine tools optimizes their workflow by using a central storage area for all the tools for all their machines instead of a manual storage warehouse with racks[4]. Such storage is often combined with maintenance and pre-setting of the tools. Complex tools are assembled from available components such as empty tool holders, adapters, cutting plates, … Depending on the number and variety of machine tools, on the variety of parts to be machined, … this storage of tools and tool components can become very complex and has to be organized and planned properly.

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Multiple automated Storage and retrieval system are usable but not all of them are appliable for storing Small and medium sized products such as machine tools. [5,6] However, 2 Types of automated storage and retrieval machines are appliable for this application: The Vertical Carousel storage Machines (VCM's) and Vertical Lift storage Machine (VLM).

VCM's are used since decades for physical storage. Large trays are mounted on a carrousel system that rotates in a vertical plane to transport a tray to the level of an operator [7]. Tools and components are picked from that tray and the next tray is ordered. Since all trays move simultaneously, movements are slow.

Figure 1: tray carrying complete tools

This research is on the use of VLM's for storage of tools and tool components and how different storage strategies will affect the total capacity. In a VLM parts are stored in trays as in VCM's. However, trays are moved individually instead of moved simultaneously. An automated lift loads an individual tray at picking level, transports that tray to a storage location and transports the next tray to the picking level [8]. VLM's are available for tray sizes from 0,6m by 1m up to trays of 1,2m by 5m having a loading capacity up to 1000kg. In some cases, a VLM can reach up to 30m of height and contain up to 400 trays but most VLM's are 5 to 8 m high.

Apart from the number of trays and the size of the trays, VLM's may differ in architecture of both lift the picking zone and influence the total capacity of a VLM in terms of number of picks that can be done per hour by an operator. The number of picks an operator can do for a certain architecture is called the pick capacity and is usually calculated in picks/hour.

For VLM's and VCM's throughput capacity models already exists [9,10,11,12,13], but they can only calculate how fast trays can be delivered to a pick opening when products need to be picked from all the trays. This gives an indication which configuration is faster for general applications and how many machines need to be grouped toghether to have a higher pick capacity. [12] The throughput capacity in these models is calculated based on the average time to deliver all the trays to a fixed delivery position, independent of the chosen architecture or storing strategy. This approach is only applicable when products are randomly stored in all installed trays.

The pick capacity model described in this paper will be able to calculate how much time is needed to retrieve a certain number of cutting tools which can be used in further machine loading problems. In the model five different VLM architectures are modelled in combination with three different storing strategies specified for cutting machine tools.

Nomenclature related to machining tools

tool components:

- Tool holder: Empty collet that can be mounted into a machine tool and where one or more cutting tool(s) must be inserted before it can be used.
- Tool adaptor: precision part to be mounted on the holder for specific cutting operations.
- Tool insert: insert mounted onto a tool holder or adaptor that actually cuts the material of the part during machining. Inserts are replaced when worn out.
- Cutter tool: tool that is mounted in a tool holder or adaptor and actually cuts the material. It can be grinded when worn out.

complete tools:

- Pre-set machine tool: A tool holder provided with adaptors and cutting tools, measured, and pre-set.
- Used machine tool: a machine tool that has been returned from the production plant and that most likely has been used, probably inserts need to be replaced. It has to be checked and pre-set before further use.

2. Vertical Lift Storage Machines

Both complete tools and tool components are stored in trays. Large complete tools and large tool holders are put on anti-slip mats, smaller components such as inserts are put in boxes. Separator plates divides all tools from each other.

The position of each item in the tray and the position of each tray in the VLM are known by the Warehouse Management System (WMS). When an item is needed, the WMS will select a tray containing this item and the VLM will transport this tray and make it available at the picking level. This can be done in different ways depending on the mechanical construction of the VLM. In this research five different architectures are compared:

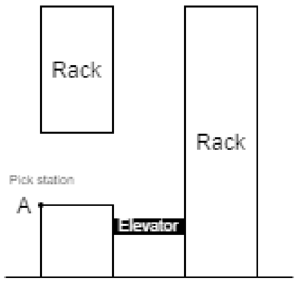

Figure 2: Single Bay VLM

2.1. Single bay VLM

The single bay VLM, (Figure 2), uses a single elevator that delivers a tray straight on the picking level. Picking is performed by an operator (or in future a cobot), the tray is loaded onto the elevator and transported to a storage position. and 1 pick station where one tray can be delivered at the same time. Basically, transports of trays and picking are not performed simultaneously.

2.2. Double bay VLM

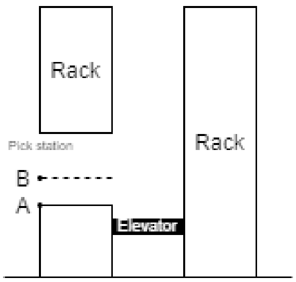

Figure 3: Double Bay VLM

The double bay VLM (Figure) also uses a single elevator but it can deliver the tray at two levels suitable for picking. Trays are alternately delivered on each picking position. As soon as all items are picked from the current tray, this tray is loaded on the elevator and transported to a storage position. Meanwhile the operator continues picking from the tray in the other picking position. While picking goes on, the elevator can deliver the next tray in the empty picking position.

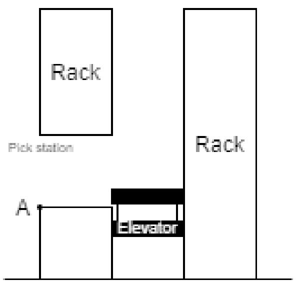

Figure 4: Double Extractor VLM

2.3. Double extractor VLM

The double extractor VLM (Figure 4) uses a single double decker elevator. One deck is used to fetch a tray in its storage position. The elevator moves towards the picking level and the second empty deck is positioned to load the tray currently being picked from. As soon as picking is completed, this tray is loaded onto the empty deck, and the next tray is delivered in the picking zone from the first deck. The tray in the second deck is stored and yet another tray is loaded on the elevator. This means that the picking is interrupted only during the loading and unloading of the trays on and from the elevator, not during the vertical travelling of the elevator.

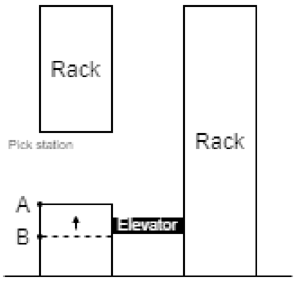

Figure 5: Buffer VLM

2.4. Buffer VLM

In a buffer VLM (Figure 5) the next tray is delivered by the elevator in a buffer position underneath the picking position. When picking from the current tray is completed, this tray is loaded onto the elevator and the tray in the buffer moves upwards to the picking position. While the operator starts picking, the elevator moves upwards, stores the previous tray, retrieves the next one and delivers it to the buffer position. Obviously in case of a short pick and a high storage position, picking will be completed before the next tray is delivered in the buffer position.

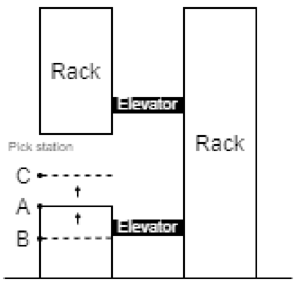

Figure 6: Independend VLM

2.5. Independent VLM

The independent VLM (Figure 6) uses 2 independent elevators and a buffer system as in the buffer VLM. The vertical transport of trays can be divided over two carriers. Any empty storage position can be used to drop a tray by one elevator to be retrieved by the other afterwards. Obviously, delivery time of trays in the picking zone can be reduced and so is the picker idle time.

3. Process types

When picking items from a VLM to deliver complete machine tools to the machines, 3 types of workflow processes can occur:

A: pick and dispatch

B: pick, prepare and dispatch
C: pick, prepare and drop in VLM

3.1. Pick and dispatch – A

Some general-purpose tools and some tools for repetitive specific operations are stored as complete tools in the VLM. Both pre-set machine tools carrying new inserts and used machine tools carrying inserts with a significant remaining tool life are stored in the VLM. When picked for effective use, the picker inspects the tool visually and dispatches the tool for transport to the machine in the workshop. The picker has all information and distinctive picking aids at his disposal and must pick just one single item from a single tray. In almost all cases such a task can be performed very fast, and it is expected that the "speed" of the VLM strongly influences the number of tools that are dispatched. Increasing the percentage of type A processes by storing more complete tools can increase the picking capacity of the system but the investment cost in tools will increase as well.

3.2. Pick, prepare and dispatch – B

The complete tool to be dispatched to the workshop has to be assembled by the picker. He must pick distinctive items from one or more trays, most often including one tool holder, one or more adaptors and either one cutter tool or several identical tool inserts. After assembly the complete tool has to be pre-set. This can be done semi-automatically or has to be done manually. Actual tool dimensions have to be stored either on the tool or in a database accessible by the machine in the workshop. After a last visual inspection, the complete tool can be dispatched to the workshop. Obviously, the total time spent by the operator in a type B process is far more than in a type A process. In most cases the picker will not start assembling the tool until all items are picked, meaning that the "speed" of the VLM to deliver all trays needed is important. After picking the last item, the VLM has plenty of time to fetch the first tray for the next tool.

3.3. Pick, prepare and drop – C

In some cases, a complete tool that has been inspected and pre-set, is for some reason not dispatched to the workshop, e.g., because the transport cart is not available, because the local tool storage of the machine is full, because production planning is modified, … The picker must perform all actions as in process B, but the complete tool is dropped in the VLM. This means that a tray with an empty tool position has to be provided by the VLM. Preparation of the next order as in process B is not possible.

3.4. Remark

In this research only processes A, B and C are considered. After checking in three workshops, it is concluded that all processes apart from replenish the items and add new items in the VLM, can be categorized within these three types as long as "prepare" is interpreted in the broadest sense.

4. Storing strategies

The numbers of trays that need to be delivered to the picking area depends on the storage location of the items that need to be picked. If all items are available in a single tray only this single tray has to be delivered to complete the order. Therefore, the actual storing strategy in combination with the process types that occur, will strongly influence the performance of the VLM and the dispatching of tools. The calculation model built in this research is able to evaluate 3 distinctive storing strategies in a VLM:

- S1: Storing per category of item
- S2: Storing per machine
- S3: Storing partial mixed

4.1. Storing per category – S1

6 main categories of items are considered:

- tool holders
- tool adaptors
- tool inserts
- cutter tools
- complete pre-set machine tools
- complete used machine tools

When storing per category, each tray contains items of one single category. For most categories several trays must be used. There are no reserved storage positions for trays per category, meaning that successive trays can contain other item types. A VLM can contain also empty trays. Empty trays are considered not to be reserved for a specific category.

4.2. Storing per machine – S2

For each machine in the workshop a number of trays are reserved. Most trays contain items from multiple categories. Identical items are stored in several trays. Obviously this storing strategy makes sense if mostly complete pre-set or used machine tools have to be stored and only a limited number of tools are used on several machines.

4.3. Partially mixed storing – S3

Some tools can be used on multiple machines, some tool adaptors fit only one type of tool holder, some inserts are used on a specific machine only and that machine needs a specific tool holder, …. Therefore, items that are used together are clustered, meaning that they are always stored in the same tray. This means that part of such a tray can have antislip mats for complete tools and part of the tray can carry boxes for components.

5. picking capacity model

The time needed to retrieve all tools for a number of jobs depends on the number of trays that need to be delivered by the VLM in the picking zone and the time the operator spends while a tray is available. The number of trays that must be delivered is determined by the storing strategy and the number items stored per tray. In table 1 the number of trays reserved for each product category and for each strategy are represented.

Nomenclature related to picking capacity model

$T_{pick}(tot)$:The total pick time
T_A : The time to complete one process of type A
a : The number of processes A
T_B : The time to complete one process of type B
b : The number of processes B
T_c : The time to complete one process of type C
c : The number of processes C
ho : The number of trays reserved for tool holders
ad : The number of trays reserved for tool adapters
in : The number of trays reserved for tool inserts
ct : The number of trays reserved for cutter tools
pmt : The number of trays reserved for complete pre-set machine tools
umt : The number of trays reserved for used machine tools
m : The number of machines used
m_1 : The number of trays reserved for storing items specific for each machine
m_{all} : The number of trays reserved for storing items for all machines = m.m$_1$
n_{ho} : The number of tool holders that need to be picked
n_{ad} : The number of tool adapters that need to be picked
n_{in} : The number of inserts that need to be picked
n_{ct} : The number of cutter tools that need to be picked
n_{pmt} : The number of prepared machine tools that need to be picked
n_{umt} : The number of used machine tools that need to be picked
i_{XY} : The number of trays that need to be delivered for process X to pick product of category Y
j_{XY} : The number of products that need to be picked from the tray for process X to pick product of category Y

Table 1.Tray reservation matrix

Number of trays reserved for tool type	S1	S2	S3
ho	$m/2$	0	m
ad	$m/3$	0	m
in	$m/4$	0	m
ct	$m/4$	0	m
pmt	$m/2$	0	$m/2$
umt	$m/2$	0	$m/2$
m_1	0	2	0
m_{all}	0	$m.m_1$	0

With the number of trays for each category defined (Table 1), the number of products that need to be picked per tray can be calculated and is determined by 2 factors: (i) the number of products that need to be picked and (ii) the number of trays where the products are stored in.

Assuming that all the products that need to be picked are distributed evenly over the number of trays they can be picked from, 2 cases are possible: In a first case, the number of products that need to be picked is lower then the number of possible trays where they can be picked from. In this case not all possible trays need to be delivered. The number of trays that need to be delivered I equal toe the number of products that need to be picked and only 1 product will be picked per tray. In the second case, more products than the number of trays that are reserved need to be picked. In that case all the possible trays must be delivered, and multiple products are taken from each tray. The number of trays that need to be delivered and how many products that need to be picked from each tray is showed in Table 2.

Table 2. Tray and pick separation

	S1 and S3	S2
i_{ho}	$\begin{cases} n_{ho}, if\ n_{ho} < ho \\ ho, otherwise \end{cases}$	$\begin{cases} n_{ho}, if\ n_{ho} < m_1 \\ m_1, otherwise \end{cases}$
j_{ho}	$\begin{cases} t_p(ho), if\ n_{ho} < ho \\ (n_{ho}/ho).t_p(ho), otherwise \end{cases}$	$\begin{cases} t_p(ho), if\ n_{ho} < m1 \\ (n_{ho}/m1).t_p(ho), otherwise \end{cases}$
i_{ad}	$\begin{cases} n_{ad}, if\ n_{ad} < ad \\ ad, otherwise \end{cases}$	$\begin{cases} n_{ad}, if\ n_{ad} < m_1 \\ m_1, otherwise \end{cases}$
j_{ad}	$\begin{cases} t_p(ad), if\ n_{ad} < ad \\ (n_{ad}/ad).t_p(ad), otherwise \end{cases}$	$\begin{cases} t_p(ad), if\ n_{ad} < m1 \\ (n_{ad}/m1).t_p(ad), otherwise \end{cases}$
i_{in}	$\begin{cases} n_{in}, if\ n_{in} < in \\ in, otherwise \end{cases}$	$\begin{cases} n_{in}, if\ n_{in} < m_1 \\ m_1, otherwise \end{cases}$
j_{in}	$\begin{cases} t_p(in), if\ n_{in} < in \\ (n_{in}/in).t_p(in), otherwise \end{cases}$	$\begin{cases} t_p(in), if\ n_{in} < m1 \\ (n_{in}/m1).t_p(in), otherwise \end{cases}$
i_{ct}	$\begin{cases} n_{ct}, if\ n_{ct} < ct \\ ct, otherwise \end{cases}$	$\begin{cases} n_{ct}, if\ n_{ct} < m_1 \\ m_1, otherwise \end{cases}$
j_{ct}	$\begin{cases} t_p(ct), if\ n_{ct} < ct \\ (n_{ct}/ct).t_p(ct), otherwise \end{cases}$	$\begin{cases} t_p(ct), if\ n_{ct} < m1 \\ (n_{ct}/m1).t_p(ct), otherwise \end{cases}$
i_{pmt}	$\begin{cases} n_{pmt}, if\ n_{pmt} < pmt \\ pmy, otherwise \end{cases}$	$\begin{cases} n_{pmt}, if\ n_{ho} < m_1 \\ m_1, otherwise \end{cases}$
j_{Apmt}	$\begin{cases} t_p(pmt), if\ n_{pmt} < pmt \\ (n_{pmt}/pmt).t_p(pmt), otherwise \end{cases}$	$\begin{cases} t_p(pmt), if\ n_{pmt} < m1 \\ (n_{pmt}/m1).t_p(pmt), otherwise \end{cases}$

5.1. Pick capacity model for process A

For process A, where a number of prepared machine tools are picked, the total time to pick n_A tools is calculated by:

$$\begin{aligned} T_A &= i_{Apmt}.(t_{deliver} + j_{Apmt}.t_{pick}(pmt)) \\ With &: n_{pmt} = n_a \end{aligned} \quad (1)$$

5.2. Pick capacity model for process B

For process B, multiple items need to be picked to prepare one prepared machine tool: one Tool holder, one Tool adapter and one cutter tool or a number of tool inserts. The time to pick n_B tools is:

$$\begin{aligned} T_B &= i_{ho}.(t_{deliver} + j_{ho}.t_{pick}(ho)) \\ &+ i_{ad}.(t_{deliver} + j_{ad}.t_{pick}(ad)) \\ &+ i_{ct}.(t_{deliver} + j_{ct}.t_{pick}(ct)) \\ With&: n_{ho} = n_B \\ n_{ad} &= n_B \\ n_{ct} &= n_B \end{aligned} \quad (2)$$

5.3. Pick capacity model for process C

Process C is identical to process B but the prepared machine tools need to be dropped back inside the VLM. Dropping an item in a VLM is the reverse process of a picking process. Therefore the calculated time for process A is assumed to be the same as the time to drop a prepared machine tool back inside the VLM. The time to prepare and drop back n_C tools is:

$$\begin{aligned} T_C &= n_C.T_B + n_C.T_A \\ With&: n_A = n_C \\ n_B &= n_C \end{aligned} \quad (3)$$

5.4. Pick time

To be able to calculate the total time to perform an order the pick time per item need to be calculated. When multiple items are picked, the operator is assumed to pick these items one by one. This is the preferred method to avoid mistakes during picking or placing. Moreover in case of larger items to be picked, such as some tool holders or adaptors, the operator cannot manipulate more than 1 item at the same time.

The exact pick time depends on multiple factors such as the exact location of the item in the tray, the walking distance between pick location and drop location. Since the aim of this calculation model is to compere the overall pick capacity of a VLM for various storing strategies, the exact specific pick time per item is not used. Instead, a constant average pick time that covers most of the products pick time is used. These values are represented in Table 3

Table 3. Pick times per product category

Product category	Pick time (s)
Tool holders	15
Tool adapters	10
Tool Inserts	10
Cutter tools	10
Pre-set machine tools	15

5.5. Throughput calculations

With the number of trays required to complete an order defined and the total pick time per tray also defined the time to deliver all the trays to the pick opening can be calculated. This is done based on the throughput models provided in [6]. In these models the number of trays per hour that a certain configuration can process is calculated based on the following formula:

$$T_{tot} = T_{FC} + n.T_{DC} + T_{LC} \quad (4)$$

Where T_{FC} is the time to retrieve the first tray, T_{DC} is the time to pick a tray, put it back inside the VLM and deliver the next tray to the pick opening and T_{LC} the time to put away the last tray. Since the operator does not need to wait until the last tray is being put away, the effective time used in this calculation model is:

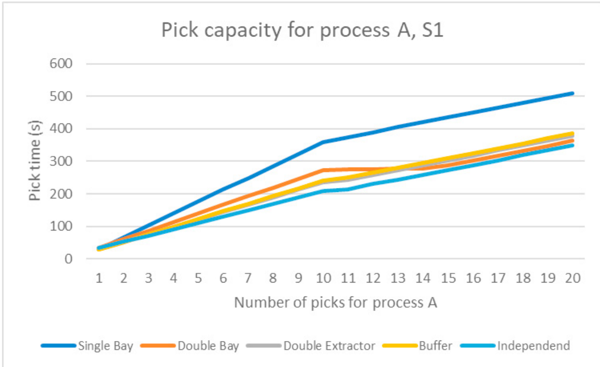

Figure 7: Pick capacity for process A, S1

$$T_{tot\,XS} = T_{FC\_XS} + n.T_{DC\_XS} \quad (5)$$

Where X is the selected configuration and S is the chosen storage strategy.

6. Results

The different configurations and storing strategies are compered by calculating the total pick capacity for each configuration and storing strategies with input parameters showed in table 4. The pick capacity results are showed in tables in A.1 ,A.2 and A.3 and some data is visualized in

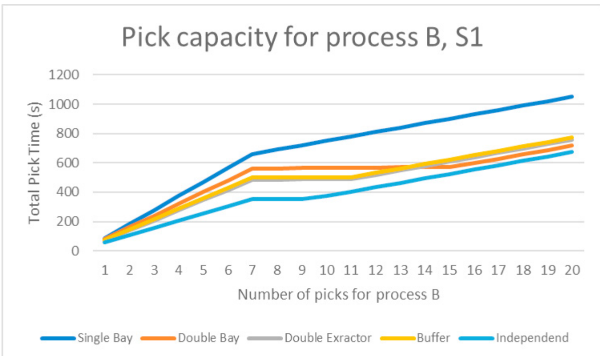

Figure 8: Pick Capacity for process B, S1

Figures 8,9 and 10.

Table 4. input parameters

Product category	
m	10 machines
VLM height	5m

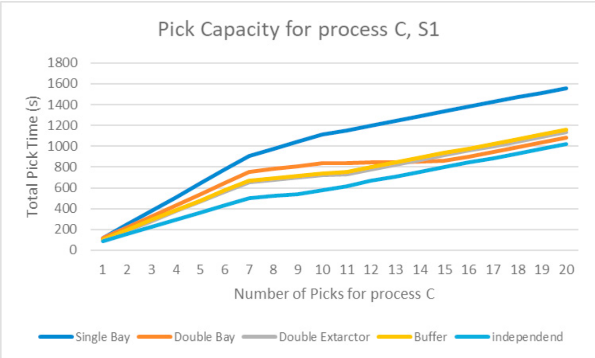

Figure 9: Pick Capacity for process C, S1

6.1. observations between different configurations

A first observation is that the single bay VLM is significant slower than all the other configurations for all processes and that the Independent VLM is always the fastest configuration, but that the differences between the independent VLM and the other configuration is lower when the number of picks increases. The difference is more significant for lower number of picks than for a higher number of picks. A second observation is that for some configurations, such as the Buffer VLM, the total pick time does not increase. The reason that it does not increase is that the VLM is, for that order, slower than the operator to pick the products. This is considered as ineffective cause the operator must wait for the VLM to deliver the next tray to the opening.

Remark: The Single bay VLM is an exception on this cause here the operator always has to wait for the VLM to deliver the next tray.

6.2. Observations between different storing strategies

A first observation is that the total pick time for Process A, S1 and S3 are the same. This is because the number trays where the products can be picked from are exactly the same. Thus, there is no difference between S1 and S3 for process A.

A second observation is that the difference between the different storing strategies are lower for the independent VLM then for the single bay VLM.

A third observation is that the strategy S2 is significant faster for Process A, but not significant faster for processes B and C.

7. Conclusions

In this paper the pick capacity of different VLM architectures and different storing strategies has been studied for storing machine tools inside a vertical storage system.

The pick capacity model can be used to calculate the tool retrieval time and comparing different VLM architectures and storage strategies but also to evaluate the influence of the number of cutting machines and pick time per product on the pick capacity.

The calculations prove that the independent VLM is considerable faster than the other configurations and is less effected by the storage strategy then the other configurations. If a Storing strategy must be chosen storing strategy 2, storing all products related to 1 machine in a number of tray, is significant faster then the other storing strategies.

Further research can focus on 2 topics: the first one is calculating the effective pick time for each tool instead of using an average time per tool, determined by observing operators. In this model the weight, size, of each tool must be included for an accurate calculation. The other topic is to optimize the relative location of different tools in one tray in such a way that the total pick time per tray can be reduced. This could be achieved by locating tools that are frequently picked together close to each other in the same tray instead of putting them into 2 separate trays.

Appendix A. Model results

A.1. Results for process A

Table 5. Total pick time for process A,S1

n_A	Single bay (s)	Double bay (s)	Double extractor (s)	Buffer (s)	Independent (s)
1	28	33	28	28	33
5	175	140	120	122	110
10	360	273	236	240	207
15	435	288	303	310	274
20	510	363	378	385	349

Table 6. Total pick time for process A,S2

n_A	Single bay (s)	Double bay (s)	Double extractor (s)	Buffer (s)	Independent (s)
1	28	33	28	28	29
5	65	60	51	52	47
10	80	68	65	66	62
15	95	83	80	81	77
20	110	98	95	96	92

Table 7. Total pick time for process A,S3

n_A	Single bay (s)	Double bay (s)	Double extractor (s)	Buffer (s)	Independent (s)
1	28	33	28	28	33
5	175	140	120	122	110

10	360	273	236	240	207
15	435	288	303	310	274
20	510	363	378	385	349

A.2. Results for process B

Table 8. Total pick time for process B,S1

n_B	Single bay (s)	Double bay (s)	Double extractor (s)	Buffer (s)	Independent (s)
1	87	81	69	75	56
5	182	161	138	145	106
10	278	241	208	216	155
15	373	321	277	287	204
20	469	401	346	357	253

Table 9. Total pick time for process B,S2

n_B	Single bay (s)	Double bay (s)	Double extractor (s)	Buffer (s)	Independent (s)
1	87	81	69	75	56
5	182	161	138	145	106
10	212	166	143	146	119
15	242	171	169	173	149
20	272	193	199	203	179

Table 10. Total pick time for process B,S3

n_B	Single bay (s)	Double bay (s)	Double extractor (s)	Buffer (s)	Independent (s)
1	43	48	43	43	44
5	95	83	80	81	77
10	125	113	110	111	107
15	155	143	140	141	137
20	185	173	170	171	167

A.3. Results for process C

Table 11. Total pick time for process C,S1

n_C	Single bay (s)	Double bay (s)	Double extractor (s)	Buffer (s)	Independent (s)
1	115	114	97	103	89
5	247	221	189	197	158
10	380	327	282	291	226
15	512	434	374	385	295
20	645	540	467	479	364

Table 12. Total pick time for process C,S2

n_C	Single bay (s)	Double bay (s)	Double extractor (s)	Buffer (s)	Independent (s)
1	115	114	97	103	85
5	247	221	189	197	152
10	292	234	209	212	180
15	337	254	249	254	225
20	382	291	294	299	270

Table 13. Total pick time for process C,S3

n_C	Single bay (s)	Double bay (s)	Double extractor (s)	Buffer (s)	Independent (s)
1	101	111	101	101	102
5	220	196	190	192	183
10	295	271	265	267	258
15	370	346	340	342	333
20	445	421	415	417	408

CRediT author statemen Validation

Pieter Vanhauwermeiren: Conceptualization, Methodology, Software, Investigation, Writing -Original Draft. Marc Juwet: Conceptualization, Writing -Original Draft, Writing -Review & Editing, Visualization, Supervision. Eric Demeester: Supervision.

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