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Scheduling in the e-commerce era: New scheduling problems in order fulfilment and warehousing

Scheduling Seminar

Chair of Operations Management
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Evolution of e-commerce and warehousing, and the impact on scheduling research

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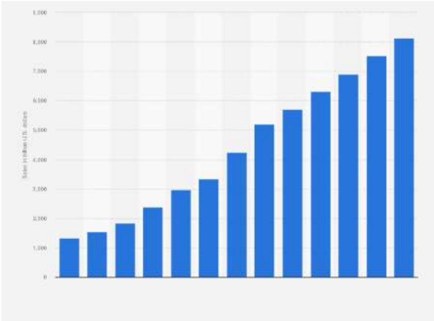
[Source: BBC]

Jane Snowball (then 72) ordered groceries via TV and phone line in 1984

[Source: Statista]



Tremendous growth of e-commerce sales

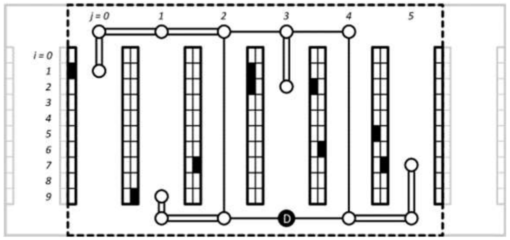
[Source: Interlake Mecalux]

Traditional warehouse

[Source: Zalando]

E-commerce warehouse of German fashion retailer Zalando

[Source: Goeke and Schneider, 2019]



Picker-to-parts warehouse: Picker routing

[Source: Vanderlande]

Parts-to-picker warehouse: Order fulfillment scheduling

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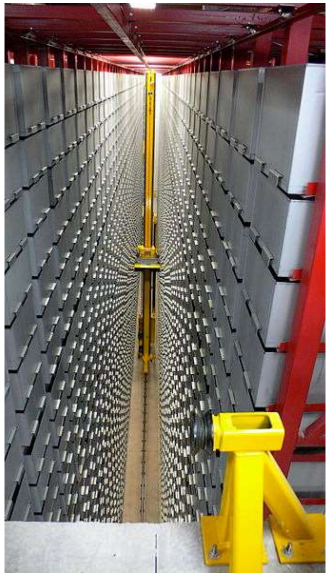
Automated storage and retrieval system (ASRS)



[Source: Wikipedia]

[Source: Bastian Solutions]

[Source: Wikipedia]

[Source: Swisslog]

Picking workstation

[Source: Vanderlande]

Shipping area

[Source: Fundamental Technologies]

Conveyor system

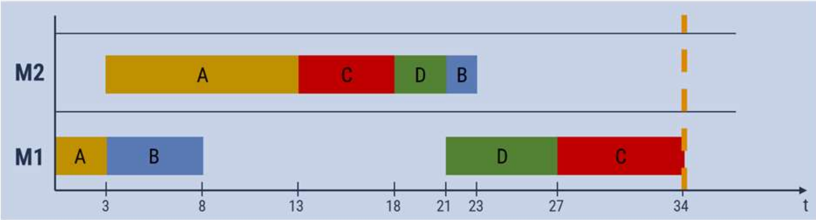
Agenda

- Peculiarities of order fulfillment scheduling
- Classification scheme
- Four examples:
  - Warehouse setup
  - Order fulfillment scheduling problem
  - Selected results
- Outlook

[Source: RightHand Robotics]

Relation machine scheduling and order fulfillment scheduling

Machine scheduling (MS)



vs.

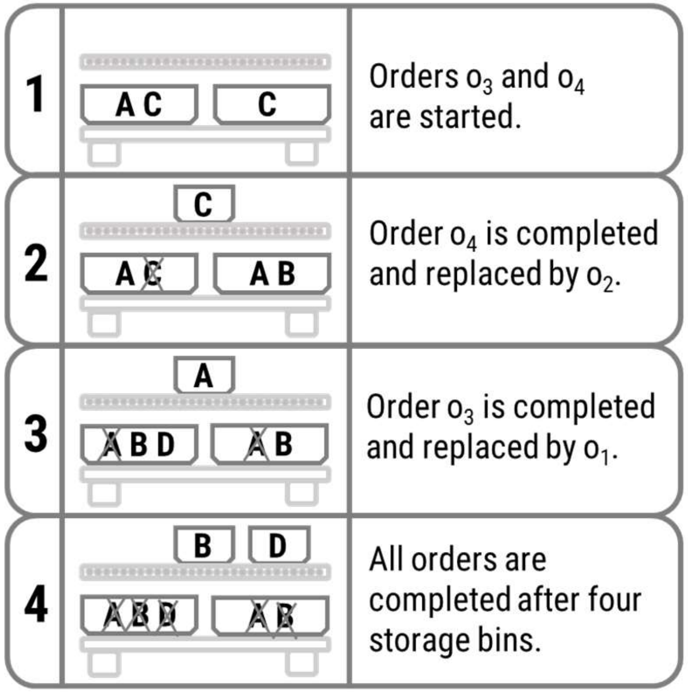
Order fulfillment scheduling (OFS)

[Source: Vanderlande]

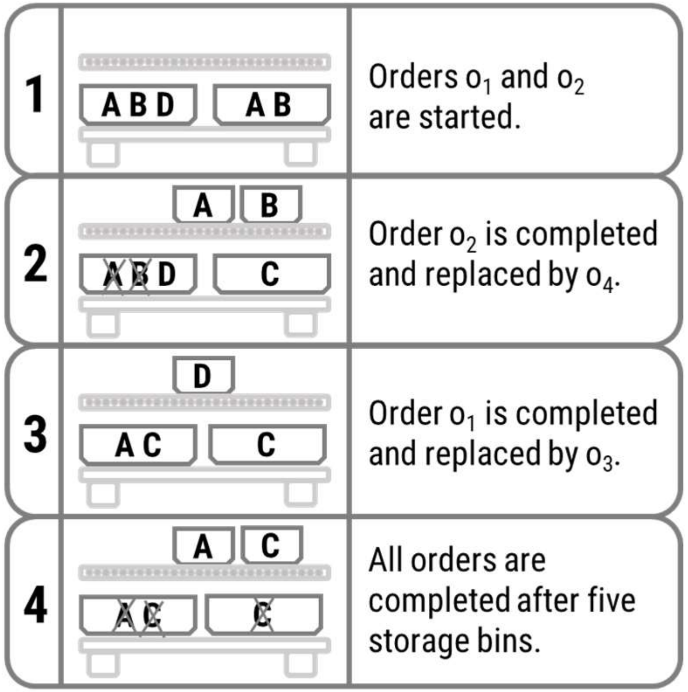
- Input-output process:
  - MS: Input: Jobs –> Output: Products
  - OFS: Input: Bins with many SKUs (stock keeping units) –> Output: customer orders
- Relation among input and output:
  - MS (single or parallel machine): 1:1 – one job –> one product
  - MS (Job shop or flow shop): 1:n – multiple jobs –> one product
  - OFS: n:m – each SKU bin can contribute to multiple orders and each order requires multiple SKU bins for completion
- Batching:
  - MS (default): one job per machine at a time
  - OFS: Parallel batching: Multiple SKU bins and/or customer bins in parallel
- OFS: Synchronization problem of SKU bins with customer bins to improve order throughput

Example for order fulfillment scheduling

[Source: Dematic]



Solution (a)



Solution (b)

3-field notation: [α (Inbound stream) | β (Outbound stream) | γ (Objective)]

α_1	$\circ$	only a single SKU bin at a time
capacity for parallel SKU bins	k	$k > 1$ SKU bins in parallel
α_2	$\circ$	only one SKU per bin
bin composition	mix	multiple SKUs per bin
α_3	$\circ$	part of optimization problem
arrival sequence	fix	already fixed
α_4	$\circ$	all bins carry enough pieces
bin inventory	pieces	limited number of pieces in the SKU bins

[Source: Dematic]

$\alpha_1 = \circ$: single SKU bin

[Source: SSI Schäfer]

$\alpha_1 = k$: multiple SKU bins in parallel access

Classification of order fulfillment scheduling

3-field notation: [α (Inbound stream) | β (Outbound stream) | γ (Objective)]

α_1	$\circ$	only a single SKU bin at a time
capacity for parallel SKU bins	k	$k > 1$ SKU bins in parallel
α_2	$\circ$	only one SKU per bin
bin composition	mix	multiple SKUs per bin
α_3	$\circ$	part of optimization problem
arrival sequence	fix	already fixed
α_4	$\circ$	all bins carry enough pieces
bin inventory	pieces	limited number of pieces in the SKU bins

[Source: Vanderlande]

$\alpha_2 = \circ$: homogeneous SKU bins

[Source: Amazon]

$\alpha_2 =$ mix: heterogeneous inventory pods

Classification of order fulfillment scheduling

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3-field notation: [α (Inbound stream) | β (Outbound stream) | γ (Objective)]

β_1 capacity for parallel customer bins	1	only a single customer bin at a time
	∘	multiple customer bins in parallel
β_2 order composition	1-SKU	each order demands only a single SKU
	∘	each order may demand multiple SKUs
β_3 processing sequence	∘	part of optimization problem
	fix	already fixed
β_4 bin exchange	∘	random access to each customer bin
	batch	batch-wise exchange of customer bins
	seq	customer bins enter and leave concurrently
β_5 SKU availability	∘	new customer bin cannot get current SKU
	fast	new customer bin can reach current SKU

[Source: TGW Logistics Group]

$\beta_1 = 1$: Picking workstation with on active customer bin

[Source: Lightning Pick]

$\beta_1 = \circ$: Put-to-light system with many customer bins

Classification of order fulfillment scheduling

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3-field notation: [α (Inbound stream) | β (Outbound stream) | γ (Objective)]

β_1 capacity for parallel customer bins	1 ∘	only a single customer bin at a time multiple customer bins in parallel
β_2 order composition	1-SKU ∘	each order demands only a single SKU each order may demand multiple SKUs
β_3 processing sequence	∘ fix	part of optimization problem already fixed
β_4 bin exchange	∘ batch seq	random access to each customer bin batch-wise exchange of customer bins customer bins enter and leave concurrently
β_5 SKU availability	∘ fast	new customer bin cannot get current SKU new customer bin can reach current SKU

[Source: Lightning Pick]

$\beta_5 = \circ$: Manual bin exchange

[Source: Vanderlande]

β_5 =fast: Picking workstation with automated bin exchange

Classification of order fulfillment scheduling

3-field notation: [α (Inbound stream) | β (Outbound stream) | γ (Objective)]

○	minimizing the total number of SKU bins
⋆	another objective

- All objectives of traditional machine scheduling are possible.
- Reduced setup times:
  - Setup time associated with each SKU bin exchange
    - Waiting time during bin switch
    - Orientation time (e.g., perceive new put-to-light signals)
- Relief of ASRS:
  - Fewer SKU bins to be delivered relief the bin supply system
  - Each bin change is a source of potential delay (e.g., delayed robot arrival)

Literature survey

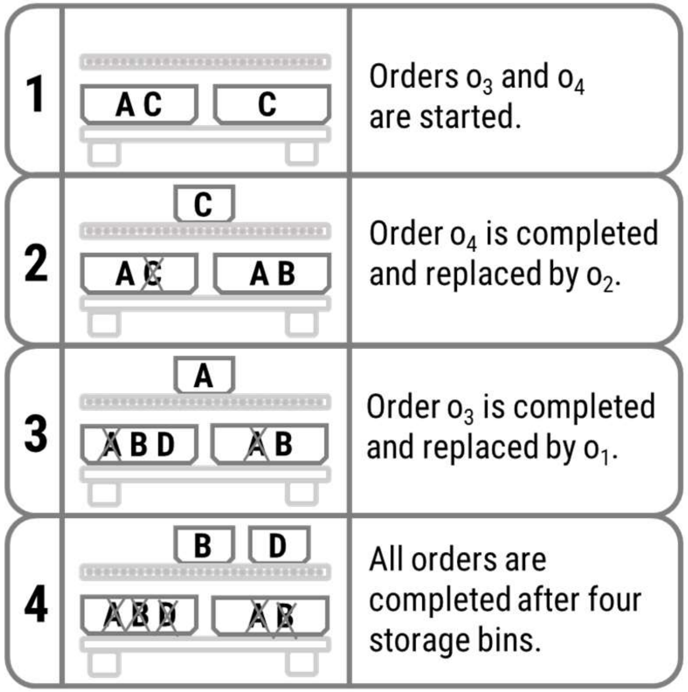
Summary of synchronization literature.

reference	tuple	Methods	application context
Asahiro et al. (2012)	[|1-SKU,fix,fast|]	–	paint shop batching
Boysen et al. (2017)	[mix|fast|]	MIP, HEU	shelf-lifting mobile robots
	[mix,fix|fast|]	EX	
	[mix|fix,fast|]	EX	
Chan et al. (2012)	[|1-SKU,fix,fast|]	EX	paint shop batching
Füßler & Boysen (2017)	[||]	MIP, HEU	inverse order picking
Füßler & Boysen (2019)	[|fast|]	MIP, HEU	ergonomic picking workstation
Nicolas, Yannick, & Ramzi (2018)	[mix|batch|]	MIP	vertical lift module
Ouzidan, Sevaux, Olteanu, Pardo, & Duarte (2022)	[|fast|]	MIP, HEU	ergonomic picking workstation
Valle & Beasley (2020)	[mix,pieces||⋆]	HEU	shelf-lifting mobile robots

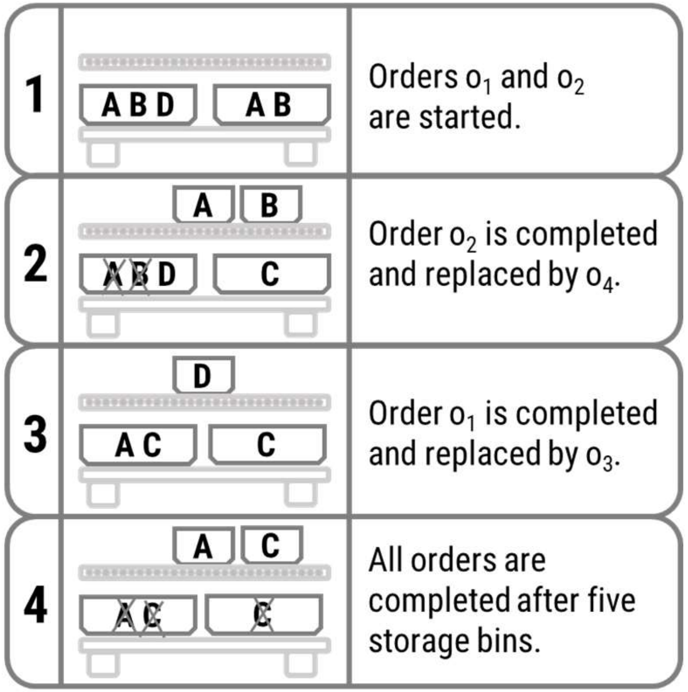
Legend: MIP: mixed integer program, EX: exact procedure, HEU: heuristic.

[|fast|] – Picking workstation

[Source: Dematic]



Solution (a)



Solution (b)

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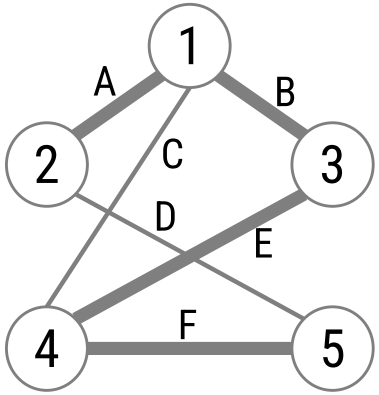
(a) HPP:

transformation



(b) [|fast|]:

o_1={A,B,C}
o_2={A,D}
o_3={B,E}
o_4={C,E,F}
o_5={D,F}
C=1

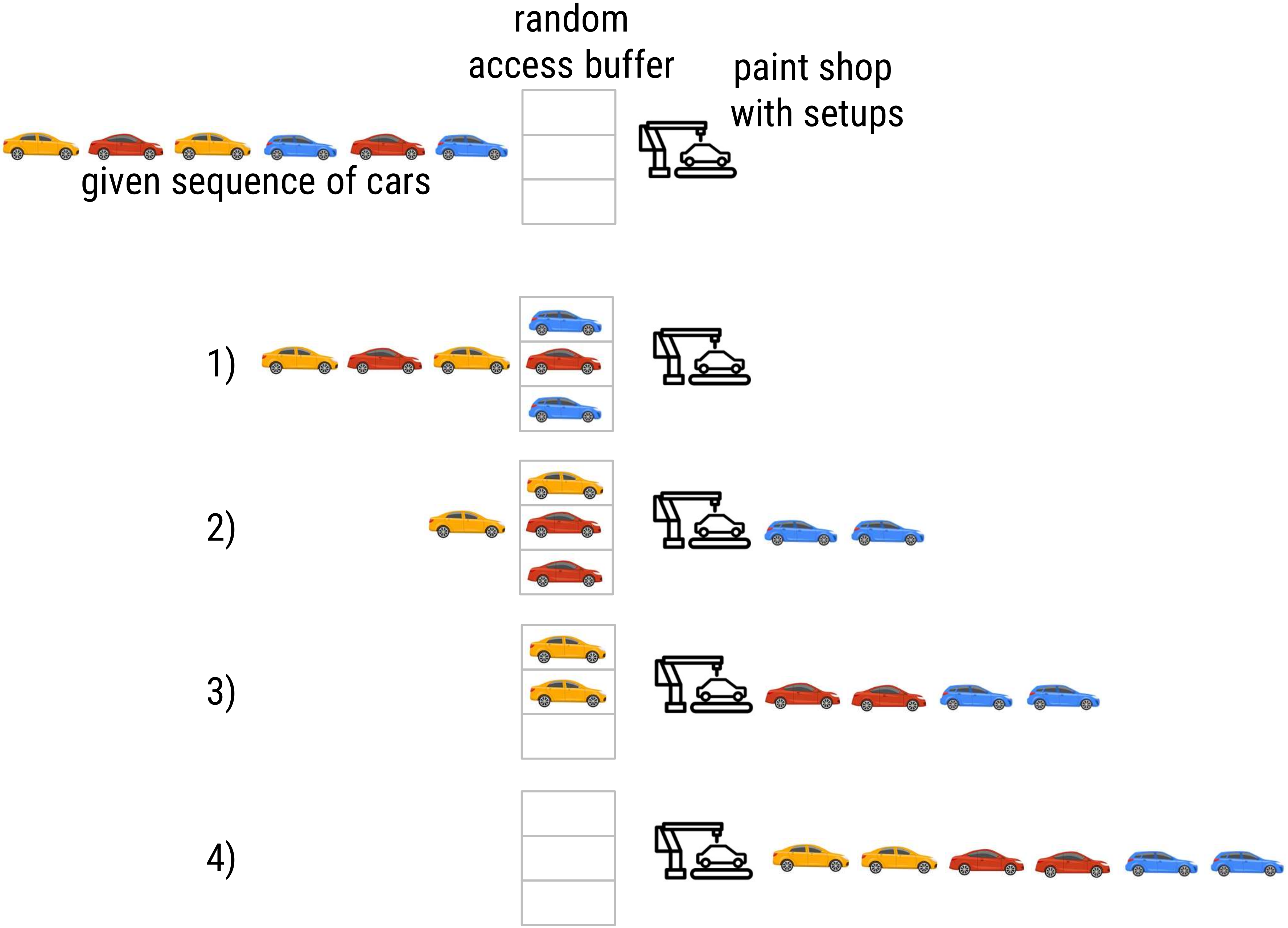
(c) solution:

order sequence

2 1 3 4 5

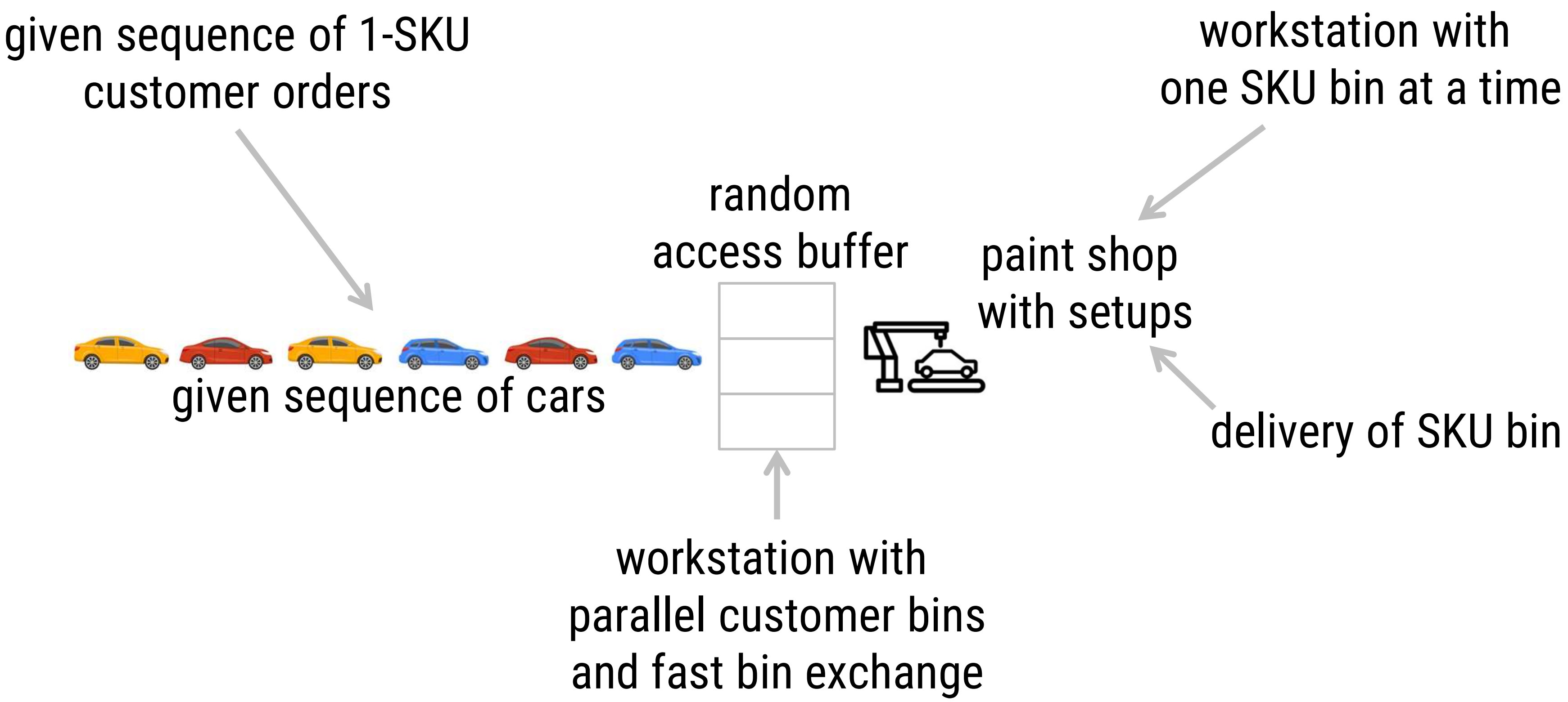
DA-ACB-BE-ECF-FD

SKU bin sequence



random
access buffer
paint shop
with setups
given sequence of cars
1)
2)
3)
4)

[|1-SKU,fix,fast|] – Paint shop batching



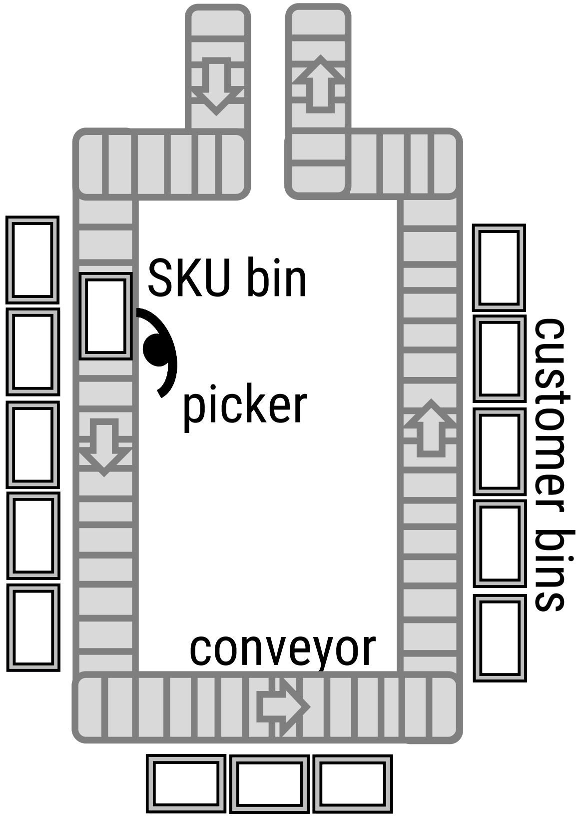
- Previous research:

  - Asahiro, Y., Kawahara, K., & Miyano, E. (2012). NP-hardness of the sorting buffer problem on the uniform metric. Discrete Applied Mathematics, 160(10-11), 1453-1464.
  - Chan, H. L., Megow, N., Sitters, R., & van Stee, R. (2012). A note on sorting buffers offline. Theoretical Computer Science, 423, 11-18.
  - Adamaszek, A., Renault, M. P., Rosén, A., & van Stee, R. (2017). Reordering buffer management with advice. Journal of Scheduling, 20, 423-442.

[|||] – Put-to-light order picking

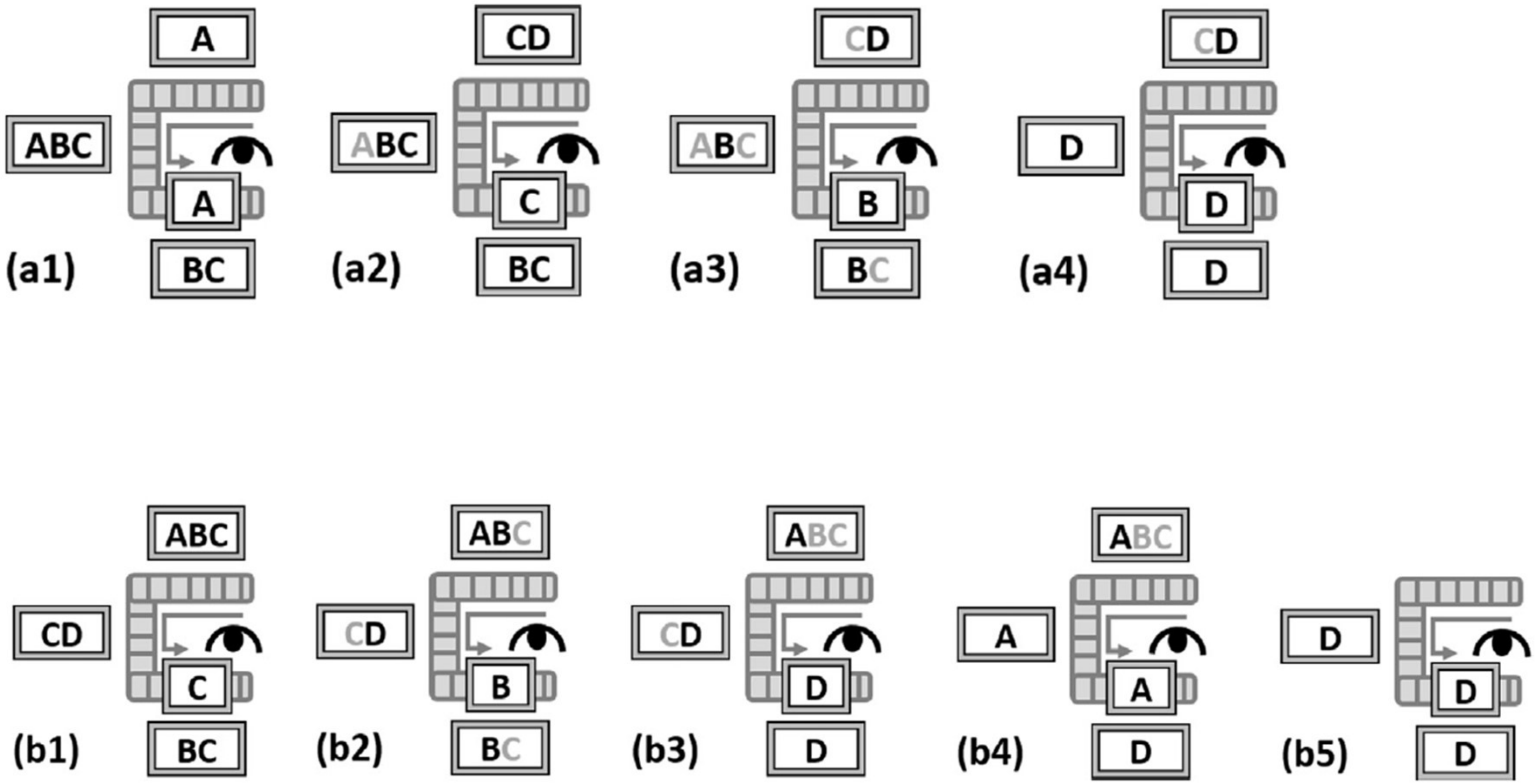
[Source: Lightning Pick]

(a) Put-to-light system Lightning Pick at apparel retailer Charlotte Russe



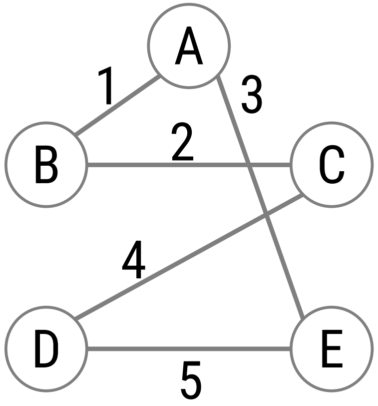
(b) System setup

[|||] – Example



A
ABC
A
(a1)
BC
CD
ABC
C
(a2)
BC
CD
ABC
B
(a3)
BC
CD
D
D
(a4)
D
ABC
CD
C
(b1)
BC
ABC
CD
B
(b2)
BC
ABC
CD
D
(b3)
D
ABC
A
A
(b4)
D
D
D
(b5)
D

(a) MCLA: transformation



k=2

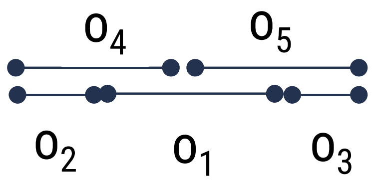
(b) [|||]:

o_1={A,B}
o_2={B,C}
o_3={A,E}
o_4={C,D}
o_5={D,E}
k=C=2

(c) solution:

Vertex labels

C^1 B^2 D^3 A^4 E^5



[mix|fast|] – Shelf-lifting mobile robots

(a) Robots lift shelves…
(here CarryPick of Swisslog)

[Source: Swisslog]

(b) and deliver them to
picking stations

[Source: Amazon]

order selection and assignment
(selects the next orders from the pool and assigns them to pick stations)

order fulfillment scheduling (OFS)
(determines the assignment of orders to batches and their processing sequence at a pick station and assigns racks to satisfy the demanded SKUs)

rack assignment problem
(assigns each stopover of racks a storage position)

robot assignment and path planning
(assigns a robot to each movement of a rack and coordinates their travel paths on the shop floor)

[mix|fast|] – Example for pick station scheduling (PSS)

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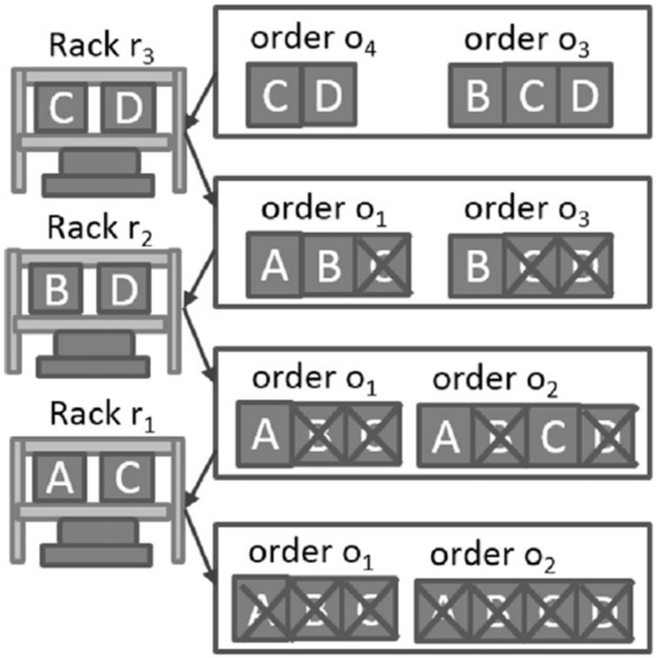
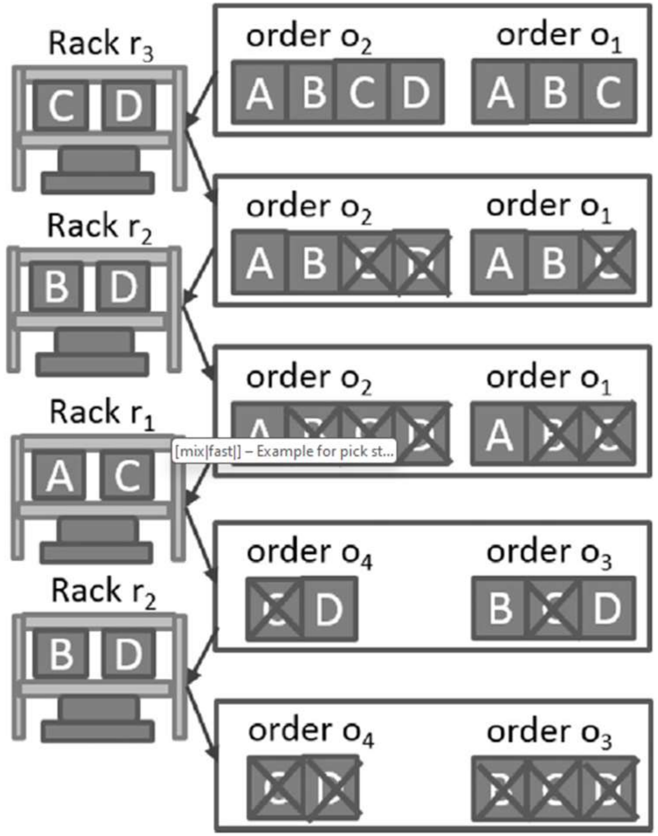
- Set $S = \{A, B, C, D\}$ an SKUs
- $n = 4$ orders: $o_1 = \{A, B, C\}$, $o_2 = \{A, B, C, D\}$, $o_3 = \{B, C, D\}$, $o_4 = \{C, D\}$
- $m = 3$ racks: $r_1 = \{A, C\}$, $r_2 = \{B, D\}$, $r_3 = \{C, D\}$
- Capacity $C = 2$



Order sequence = <o4, o3, o1, o2]
Rack sequence = <r3, r2, r1]



Order sequence = <o2, o1, o4, o3]
Rack sequence = <r3, r2, r1, r2]

[mix|fast||] – Complexity

- Decomposition
  - Solve rack sequencing for given order sequence – str. NP-hard
  - Solve order sequencing for given rack sequence – str. NP-hard

[Source: Amazon]

More complexity results

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Strongly NP-hard synchronization problems.

<table>
<tr><th></th><th>class of synchronization problems</th><th># SP</th><th>transformation from</th><th>reference</th></tr>
<tr><td>1</td><td>[∘; ∘; ∘; ∘|∘; ∘; ∘; ∘|∘]</td><td>1</td><td>min-cut linear arrangement</td><td>(Füßler & Boysen, 2017)</td></tr>
<tr><td>2</td><td>[∘; −; ∘; −|∘; ∘; ∘; ∘|∘]</td><td>4</td><td>[∘; ∘; ∘; ∘|∘; ∘; ∘; ∘|∘]</td><td>Lemma 2</td></tr>
<tr><td>3</td><td>[∘; −; ∘; −|1; ∘; ∘; −; fast|∘]</td><td>12</td><td>Hamilton path</td><td>Theorem 1</td></tr>
<tr><td>4</td><td>[∘; −; ∘; −|−; ∘; ∘; −; fast|∘]</td><td>24</td><td>Hamilton path</td><td>Corollary 1</td></tr>
<tr><td>5</td><td>[k; −; ∘; −|−; ∘; ∘; −; fast|∘]</td><td>24</td><td>[∘; −; ∘; −|−; ∘; ∘; −; fast|∘]</td><td>Corollary 11</td></tr>
<tr><td>6</td><td>[∘; ∘; ∘; ∘|∘; 1-SKU; fix; ∘; fast|∘]</td><td>1</td><td>sorting buffer problem</td><td>(Asahiro et al., 2012; Chan et al., 2012)</td></tr>
<tr><td>7</td><td>[∘; −; ∘; −|∘; −; fix; ∘; fast|∘]</td><td>8</td><td>[∘; ∘; ∘; ∘|∘; 1-SKU; fix; ∘; fast|∘]</td><td>Lemma 2</td></tr>
<tr><td>8</td><td>[∘; −; −; pieces|−; −; ∘; −; ∘|∘]</td><td>48</td><td>3-Partition</td><td>Theorem 2</td></tr>
<tr><td>9</td><td>[∘; −; −; pieces|∘; ∘; ∘; −; fast|∘]</td><td>12</td><td>3-Partition</td><td>Theorem 2</td></tr>
<tr><td>10</td><td>[k; −; −; pieces|∘; ∘; ∘; −; fast|∘]</td><td>12</td><td>[∘; −; −; pieces|∘; ∘; ∘; −; fast|∘]</td><td>Corollary 11</td></tr>
<tr><td>11</td><td>[∘; −; ∘; pieces|1; −; −; −; ∘|∘]</td><td>24</td><td>3-Partition</td><td>Theorem 2</td></tr>
<tr><td>12</td><td>[∘; −; fix; pieces|1; −; ∘; −; fast|∘]</td><td>12</td><td>3-Partition</td><td>Corollary 5</td></tr>
<tr><td>13</td><td>[k; −; fix; pieces|1; ∘; ∘; −; fast|∘]</td><td>6</td><td>[∘; −; fix; pieces|1; −; ∘; −; fast|∘]</td><td>Corollary 11</td></tr>
<tr><td>14</td><td>[∘; −; fix; pieces|∘; −; ∘; batch; −|∘]</td><td>8</td><td>3-Partition</td><td>Corollary 6</td></tr>
<tr><td>15</td><td>[k; −; fix; pieces|∘; ∘; ∘; batch; fast|∘]</td><td>2</td><td>[∘; −; fix; pieces|∘; ∘; ∘; batch; fast|∘]</td><td>Corollary 11</td></tr>
<tr><td>16</td><td>[∘; −; fix; pieces|∘; −; ∘; seq; −|∘]</td><td>8</td><td>3-Partition</td><td>Corollary 6</td></tr>
<tr><td>17</td><td>[k; −; fix; pieces|∘; ∘; ∘; seq; fast|∘]</td><td>2</td><td>[∘; −; fix; pieces|∘; ∘; ∘; seq; fast|∘]</td><td>Corollary 11</td></tr>
<tr><td>18</td><td>[∘; −; ∘; pieces|−; −; fix; −; −|∘]</td><td>48</td><td>3-Partition</td><td>Corollary 7</td></tr>
<tr><td>19</td><td>[k; −; ∘; pieces|−; ∘; fix; −; fast|∘]</td><td>12</td><td>[∘; −; ∘; pieces|−; ∘; fix; −; fast|∘]</td><td>Corollary 11</td></tr>
<tr><td>20</td><td>[∘; −; fix; pieces|∘; ∘; fix; ∘; −|∘]</td><td>4</td><td>3-Partition</td><td>Corollary 8</td></tr>
<tr><td>21</td><td>[k; −; fix; pieces|∘; ∘; fix; ∘; fast|∘]</td><td>2</td><td>[∘; −; fix; pieces|∘; ∘; fix; ∘; fast|∘]</td><td>Corollary 11</td></tr>
<tr><td>22</td><td>[∘; mix; ∘; ∘|∘; 1-SKU; −; −; −|∘]</td><td>12</td><td>set covering</td><td>(Boysen et al., 2017), Theorem 3</td></tr>
<tr><td>23</td><td>[k; mix; ∘; ∘|∘; 1-SKU; −; −; fast|∘]</td><td>6</td><td>set covering</td><td>(Boysen et al., 2017), Theorem 3</td></tr>
<tr><td>24</td><td>[∘; mix; ∘; −|∘; −; −; −; −|∘]</td><td>48</td><td>[∘; mix; ∘; ∘|∘; 1-SKU; −; −; −|∘]</td><td>Lemma 2</td></tr>
<tr><td>25</td><td>[k; mix; ∘; −|∘; −; −; −; fast|∘]</td><td>24</td><td>[k; mix; ∘; ∘|∘; 1-SKU; −; −; fast|∘]</td><td>Lemma 2</td></tr>
<tr><td>26</td><td>[−; mix; ∘; −|1; −; ∘; −; fast|∘]</td><td>24</td><td>set covering</td><td>Corollary 9</td></tr>
<tr><td>27</td><td>[k; mix; ∘; −|1; −; fix; −; fast|∘]</td><td>12</td><td>set covering</td><td>Corollary 9</td></tr>
<tr><td>28</td><td>[−; mix; ∘; −|−; ∘; −; −; −|∘]</td><td>96</td><td>set covering</td><td>Corollary 10</td></tr>
<tr><td>29</td><td>[∘; mix; fix; ∘|1; ∘; ∘; ∘; fast|∘]</td><td>1</td><td>interval scheduling</td><td>(Boysen et al., 2017)</td></tr>
<tr><td>30</td><td>[∘; mix; fix; −|−; ∘; ∘; −; fast|∘]</td><td>12</td><td>[∘; mix; fix; ∘|1; ∘; ∘; ∘; fast|∘]</td><td>Lemmas 1 and 2</td></tr>
<tr><td>31</td><td>[k; mix; fix; −|−; ∘; ∘; −; fast|∘]</td><td>12</td><td>[∘; mix; fix; −|−; ∘; ∘; −; fast|∘]</td><td>Corollary 11</td></tr>
</table>

281 out of 576 problems are shown to be strongly NP-hard.

156 out of 576 problems are solvable in polynomial time.

Synchronization problems solvable to optimality in polynomial time.

<table>
<tr><th></th><th>class of synchronization problems</th><th># SP</th><th>valid only if</th><th>reference</th></tr>
<tr><td>1</td><td>[∘; −; fix; ∘|−; 1-SKU; ∘; −; fast|∘]</td><td>12</td><td></td><td>Lemma 5</td></tr>
<tr><td>2</td><td>[∘; ∘; fix; ∘|−; 1-SKU; ∘; −; ∘|∘]</td><td>6</td><td></td><td>Lemma 5</td></tr>
<tr><td>3</td><td>[∘; ∘; ∘; ∘|−; 1-SKU; ∘; −; fast|∘]</td><td>6</td><td></td><td>Lemma 5</td></tr>
<tr><td>4</td><td>[∘; ∘; ∘; pieces|−; 1-SKU; ∘; −; fast|∘]</td><td>6</td><td></td><td>Lemma 5</td></tr>
<tr><td>5</td><td>[∘; ∘; ∘; ∘|1; 1-SKU; fix; −; −|∘]</td><td>6</td><td></td><td>Lemma 6</td></tr>
<tr><td>6</td><td>[∘; ∘; ∘; ∘|1; −; −; −; ∘|∘]</td><td>12</td><td></td><td>Lemma 7</td></tr>
<tr><td>7</td><td>[∘; −; fix; ∘|−; −; fix; −; −|∘]</td><td>48</td><td></td><td>Lemma 8</td></tr>
<tr><td>8</td><td>[∘; −; −; ∘|1; 1-SKU; −; −; ∘|∘]</td><td>24</td><td></td><td>Lemma 9</td></tr>
<tr><td>9</td><td>[∘; mix; fix; ∘|−; 1-SKU; ∘; −; ∘|∘]</td><td>6</td><td></td><td>Lemma 10</td></tr>
<tr><td>10</td><td>[∘; mix; ∘; ∘|1; 1-SKU; fix; −; fast|∘]</td><td>3</td><td></td><td>Theorem 4</td></tr>
<tr><td>11</td><td>[−; −; ∘; ∘|−; −; fix; ∘; fast|∘]</td><td>16</td><td>(a) and (b) and (c)</td><td>Corollary 12</td></tr>
<tr><td>12</td><td>[−; −; ∘; ∘|−; −; fix; seq; fast|∘]</td><td>16</td><td>(a) and (b) and (c)</td><td>Corollary 13</td></tr>
<tr><td>13</td><td>[−; −; ∘; ∘|−; −; fix; batch; fast|∘]</td><td>16</td><td>(a) and (b) and (c)</td><td>Corollary 14</td></tr>
<tr><td>14</td><td>[−; −; fix; ∘|−; −; fix; −; fast|∘]</td><td>48</td><td>(a) and (b) and (c)</td><td>Corollary 15</td></tr>
<tr><td>15</td><td>[−; −; −; ∘|−; −; fix; −; fast|∘]</td><td>96</td><td>(a) and (b) and (c)</td><td>Theorem 5</td></tr>
<tr><td>(a)</td><td colspan="4">the SKU bin capacity k is limited by a constant</td></tr>
<tr><td>(b)</td><td colspan="4">the customer bin capacity is limited by a constant</td></tr>
<tr><td>(c)</td><td colspan="4">the maximum number of SKUs required by a customer bin is limited by a constant</td></tr>
</table>

Managerial results - I

Synchronization gains in number of SKU bins deliveries in % for different workstation setups related to default case [|||] depending on different demand structures (EQ and ABC) and customer bin capacities β_1 .

case	extension	EQ			ABC		
		$\beta_1 = 1$	$\beta_1 = 3$	$\beta_1 = 5$	$\beta_1 = 1$	$\beta_1 = 3$	$\beta_1 = 5$
[|||]	–	0.00	-27.55	-35.92	0.00	-42.50	-56.61
[3||]	parallel SKU bins	-24.43	-32.60	-38.05	-48.27	-49.41	-59.86
[5||]	parallel SKU bins	-33.63	-34.45	-38.77	-61.26	-61.26	-62.10
[mix||]	mix of SKUs per bin	-2.83	-41.60	-52.26	-2.63	-50.24	-64.14
[|fix|]	given order sequence	0.00	-17.46	-27.17	0.00	-26.54	-45.51
[|batch|]	bin exchange	0.00	-8.51	-14.70	0.00	-25.00	-35.95
[|seq|]	bin exchange	0.00	-14.04	-25.31	0.00	-32.82	-44.42
[|fast|]	bin exchange	-11.54	-30.43	-36.61	-20.78	-49.21	-58.16

[Source: Vanderlande]

More bins?

- Should we have more bins?
  - Yes, more bin capacity greatly reduces the SKU bin deliveries.
  - The positive effect is especially strong for ABC orders.
  - The positive effect quickly diminishes, so that more than five is barely worth the effort.
  - Negative effect: More picker movement along the pick face.
- Should be increase the capacity for SKU bins or customer bins?
  - It does not matter.

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Synchronization gains in number of SKU bins deliveries in % for different workstation setups related to default case [|||] depending on different demand structures (EQ and ABC) and customer bin capacities β_1 .

		EQ			ABC		
case	extension	$\beta_1 = 1$	$\beta_1 = 3$	$\beta_1 = 5$	$\beta_1 = 1$	$\beta_1 = 3$	$\beta_1 = 5$
[|||]	–	0.00	-27.55	-35.92	0.00	-42.50	-56.61
[3||]	parallel SKU bins	-24.43	[illegible]	-38.05	[illegible]	[illegible]	[illegible]
[5||]	parallel SKU bins	-33.63	-34.45	-38.77	-61.26	-61.26	-62.10
[mix||]	mix of SKUs per bin	-2.83	-41.60	-52.26	-2.63	-50.24	-64.14
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[|fast|]	bin exchange	-11.54	-30.43	-36.61	-20.78	-49.21	-58.16

[Source: Vanderlande]

vs.

[Source: Amazon]

Mixed SKU bins?

- Should we mix the SKU bins?
  - Not necessarily, the positive effect is rather small.
  - Negative effect: More search effort for the picker to find the right SKU.
  - Support in warehouses: Picture of SKU on display or laser beam onto right compartment.

Managerial results - III

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Synchronization gains in number of SKU bins deliveries in % for different workstation setups related to default case [|||] depending on different demand structures (EQ and ABC) and customer bin capacities β_1 .

case	extension	EQ			ABC		
		$\beta_1 = 1$	$\beta_1 = 3$	$\beta_1 = 5$	$\beta_1 = 1$	$\beta_1 = 3$	$\beta_1 = 5$
[|||]	–	0.00	-27.55	-35.92	0.00	-42.50	-56.61
[3|||]	parallel SKU bins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[5|||]	parallel SKU bins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[mix|||]	mix of SKUs per bin	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[|fix|]	given order sequence	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[|batch|]	bin exchange	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[|seq|]	bin exchange	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[|fast|]	bin exchange	-11.54	-30.43	-36.61	-20.78	-49.21	-58.16

[Source: Vanderlande]

vs.

[Source: Lightning Pick]

Fast customer bin switches ?

- Should we invest into an automated mechanism to switch completed customer bins fast?
  - Yes, but only if a parallelization of multiple (SKU or customer) bins is not possible.

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- Order fulfillment problems appear
  - in many different parts-to-picker systems
  - with slight variation.
  - There is not much work on these problems,
  - especially from a general perspective.

[Source: Amazon]

[Source: Lightning Pick]

[Source: Vanderlande]

Outlook: Within 5-10 years, we have the fully-automated e-commerce fulfillment factory

[Source: Mecalux]

Picking robot with vacuum griper

Robotized sorting

[Source: Tompkins Robotics]

[Source: Industrial Automation]

Automated packing

Robots and machinery need advice!
We need more research on warehouse scheduling!

Thank you very much for your attention

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[Source: Amazon]

- Literature:
  - Boysen, N., Schwerdfeger, S., & Stephan, K. (2023). A review of synchronization problems in parts-to-picker warehouses. European Journal of Operational Research, 307(3), 1374-1390.
  - Boysen, N., Briskorn, D., & Emde, S. (2017). Parts-to-picker based order processing in a rack-moving mobile robots environment. European Journal of Operational Research, 262(2), 550-562.
  - Füßler, D., & Boysen, N. (2019). High-performance order processing in picking workstations. EURO Journal on Transportation and Logistics, 8(1), 65-90.
  - Füßler, D., & Boysen, N. (2017). Efficient order processing in an inverse order picking system. Computers & Operations Research, 88, 150-160.