**SUPPLEMENTAL MATERIALS**

# 8. Appendices

## 8.1 Appendix A: The economic perspective for the tier-to-tier SBS/RS

When the number of shuttles is adjusted according to the required capacity, the shuttle price is very important. If the shuttle price is too low, the process used to determine the number of shuttles has a marginal effect on the cost-effective design. In this section, the ratio of each resource to the total price is suggested (Table A1), and the effect of the process is addressed. In Table A1, the shuttle costs account for most of the total costs (more than 10 times the storage racks and seven times the buffers). This indicates that if the system can reduce just one shuttle, it will have a large effect on the costs. For example, because the total shuttle costs account for 70 % of the total costs in , approximately 7 % of the total costs can be saved whenever the number of shuttles is decreased by one.

Table A1. The approximate ratio of each resource to the total price in the tier-captive SBS/RS

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  | Shuttle (%) | Storage rack (%) | Buffer (%) | Elevator (%) |
| 1 | 10 | 56 | 70.1 | 6.1 | 9.8 | 14.0 |
| 2 | 9 | 62 | 68.6 | 6.7 | 9.5 | 15.2 |
| 3 | 8 | 70 | 66.7 | 7.3 | 9.3 | 16.7 |
| 4 | 10 | 38 | 71.5 | 4.3 | 9.9 | 14.3 |
| 5 | 9 | 42 | 70.1 | 4.6 | 9.7 | 15.6 |
| 6 | 8 | 48 | 68.3 | 5.1 | 9.5 | 17.1 |

## 8.2 Appendix B: Differences between the tier-to-tier AVS/RS and SBS/RS

Figure B1 shows the shuttle movement differences between the tier-to-tier AVS/RS and SBS/RS. As seen, the elevator always transfers the transaction with the shuttle carrier in the AVS/RS because the system does not have buffer conveyors. This means that the shuttle and the elevator cannot handle the transactions independently. Hence, there are no cases in which the transaction uses the elevator alone. On the other hand, the SBS/RS has buffer conveyors that provide the space for waiting loads. As a result, the elevator movement has two purposes. One is to transfer the shuttle from one tier to another tier, and the other is to transfer the loads to the destination (buffer conveyor) in a certain tier.

 

|  |  |
| --- | --- |
| (a) shuttle movement in tier-to-tier AVS/RS | (b) shuttle movement in tier-to-tier SBS/RS |

Figure B1. Shuttle movement differences between tier-to-tier AVS/RS and SBS/RS

Figure B2 shows the shuttle deadlock avoidance in an AVS/RS. When a potential collision presents itself, the shuttle can easily avoid the collision within one tier. In contrast, the SBS/RS requires the shuttle’s inter-tier movement because there is insufficient space to avoid a deadlock (one parallel bidirectional guide-path) (figure B3). Hence, the SBS/RS needs the system control to prevent two different shuttles from gathering in one tier. A more detailed explanation can be found in Ha and Chae (2018).

 

|  |  |
| --- | --- |
| (a) Deadlock situation in an AVS/RS | (b) Deadlock avoidance in an AVS/RS |

Figure B2. Top view of deadlock avoidance example in an AVS/RS (Ha and Chae, 2018)



Figure B3. Top view of deadlock avoidance example in an SBS/RS

## 8.3 Appendix C: Operational problem in a tier-to-tier SBS/RS

The following Figure C1 show the operational problem in a tier-to-tier SBS/RS.



|  |
| --- |
| (a) Collision point description |



|  |
| --- |
| (b) Blocking delay description |

Figure C1. Operational problems in a tier-to-tier SBS/RS

## 8.4 Appendix D: Flow of the transaction process logic (TPL)

The following Figure D1 show the flow of the transaction process logic (TPL).



|  |
| --- |
| (a) Flow of the storage transaction process logic (STPL) |



|  |
| --- |
| (b) Flow of the retrieval transaction process logic (RTPL) |

Figure D1. Flow of the transaction process logic (TPL) (Ha and Chae, 2018)

## 8.5 Appendix E: The probability of Dual Commands

In the paper, dual commands have priority over single commands. If the shuttle can process the retrieval transaction following the storage transaction, the shuttle never returns to the dwell point, but instead deals with the retrieval transaction. For example (Figure E1), Schedules 3 and 4 show a DC operation. While the shuttle processes the storage transaction (Schedule 3), the retrieval transaction (Schedule 4) occurs, and thus, after the completion of Schedule 3, the shuttle does not return to the I/O point, but instead moves directly to the bay where Schedule 4 occurs. On the other hand, Schedules 5 and 6 cannot be DC operations because the shuttle must travel to the output point to complete the retrieval transaction. Namely, all of the cases that the retrieval transaction occurs during processing storage transaction regarded as the dual command.

Figure E1. Time schedule of a shuttle carrier in the tier-captive SBS/RS

## 8.6 Appendix F: Example of the transaction process logic (basic system control)

As mentioned in Appendix A, the SBS/RS needs a new system control. In this paper, the basic system control has two functions. First, a single tier can have only one shuttle. Second, the shuttles are dynamically assigned to tiers according to the transactions (shuttles’ dynamic allocation). These functions allow the system to prevent collisions and blocking delays, as well as to operate the resources more efficiently. In this section, processing transactions are described to clarify the basic system control used in this paper. A more detailed explanation can be found in Ha and Chae (2018).

There are primarily two processing transaction cases in tier-to-tier SBS/RSes. First, if an incoming transaction arrives at the tier that has a shuttle or shuttle assignment, the transaction is handled by that shuttle. In this case, the process is the same as that of the tier-captive SBS/RS. Second, when incoming transactions arrive at a tier that does not have any shuttles, the shuttle dynamic allocation process (SDAP) begins. When this happens, the system puts the top priority on determining whether there already exists a transaction calling another shuttle because the system must prohibit multiple shuttles from gathering simultaneously in one tier. When an existing transaction has already called another shuttle in another tier, the SDAP finishes because there is no longer a need to call another shuttle. In the example (Figure F1), Tier 4 needs a shuttle to deal with Load L1 (the storage transaction). Because all shuttles (S1 through S4) are not allocated by other transactions within Tier 4, the SDAP begins. This is verified by the shuttle’s inter-tier assignment status.



|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| System status | | | | |
| Shuttle | S1 | S2 | S3 | S4 |
| Shuttle's current location | Tier 5 | Tier 3 | Tier 2 | Tier 1 |
| Shuttle's inter-tier assignment status | X | X | X | X |
| Shuttle's status | Deliver | Deliver | Deliver | Idle |

Figure F1. Beginning of the shuttle’s dynamic allocation process (SDAP) (Ha and Chae, 2018)

Next, the transaction decides which shuttle to assign. First, the system needs to sort out the deployable shuttles by excluding the shuttles that are already allocated for inter-tier movement from the candidates. Subsequently, the shuttles in idle status are also excluded. After the possible candidates are determined, the closest idle shuttle from the transaction is preferentially assigned. However, when no idle shuttles exist, the assignment is given to the shuttle with the shortest distance between the transaction origin and the current shuttle destination. In the example (Figure F1), the candidates for Load L1 are S1, S2, S3 and S4. Because none of the shuttles are allocated to other transactions, there are no previous commands for the shuttle’s inter-tier movement. This means that there is no possibility that the current command for the inter-tier movement overlaps with a previous command. However, three shuttles (S1, S2 and S3) are not in idle status. Only S4 does not have any job assignments. Naturally, S4 becomes the only candidate for the assignment, and thus, L1 assigns S4 (Figure F2(a)), and the SDAP is terminated. During the SDAP, it is crucial to decide whether a shuttle needs to be called, and this decision must be implemented by the shuttle’s inter-tier assignment status rather than the current location. In the example (Figure F2(b)), after L1 assigns S4, Load L3 (the retrieval transaction) arrives at Tier 1. At that time, although S4 is at Tier 1, L3 must bring another shuttle. Hence, the SDAP re-initiates, and the candidates that have not been assigned for inter-tier movement are determined (S1, S2 and S3). Among the candidates, S3 is reserved by L3 because it has the shortest distance between the candidate destination and L3’s position.



|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| System status | | | | |
| Shuttle | S1 | S2 | S3 | S4 |
| Shuttle's current location | Tier 5 | Tier 3 | Tier 2 | Tier 1 |
| Shuttle's inter-tier assignment status | X | X | X | O – Tier 4 |
| Shuttle's status | Deliver | Deliver | Deliver | Idle |

(a) Idle shuttle assignment example



|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| System status | | | | |
| Shuttle | S1 | S2 | S3 | S4 |
| Shuttle's current location | Tier 5 | Tier 3 | Tier 2 | Tier 1 |
| Shuttle's inter-tier assignment status | X | X | X | O – Tier 4 |
| Shuttle's status | Deliver | Deliver | Deliver | Retrieval |

(b) Example of shuttle assignment in which all shuttles have jobs

Figure F2. Example of the shuttle dynamic assignment process (SDAP) model (Ha and Chae, 2018)