DESIGN AND CONTROL OF SHUTTLE-BASED STORAGE AND RETRIEVAL SYSTEMS USING A SIMULATION APPROACH

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ABSTRACT

During recent years, Shuttle-based Storage and Retrieval Systems (SBS/RSs) have been widely applied in distribution centers and production sites to meet the increasing demand for rapid and flexible large-scale warehousing activities. Recognizing the complex service dynamics due to the use of different types of S/R devices, both the configuration design problem and operational control problem need to be studied in order to improve efficient, sustainable and robust performance of the system. An animated, data-driven and data-generated simulation model is developed to support the development of both the design and configuration methodology and operational control strategy of SBS/RS-based warehouse systems. The model enables detailed analysis of different system configurations and technology options including tier-captive and tier-to-tier, multi-deep rack designs, multi-capacity lifts, etc., and provides visualized tracking of accurately simulated service processes of the S/R devices and performance evaluation under configurable demand scenarios.

1   INTRODUCTION

An SBS/RS typically applies a number of shuttles (vehicles) and two non-passing lifts – a storage lift and a retrieval lift – for each aisle. Just like all other types of automated warehouse systems, the operations in both types of SBS/RS-based warehouse system can be described as: 1) storage operations, by which specific SKUs (stock keeping units) stored in container units (totes, bins, etc.) are delivered from system input terminals to specific storage locations (slots) in the rack; and 2) retrieval operations, by which specific SKUs stored in container units are accessed from specific slots in the rack and then delivered to system output terminals. However, unlike its traditional counterparts like crane-based automated storage and retrieval system (CBS/RS) in which a single automated mechanism takes care of all aspects of storage and retrieval operations, each S/R device in an SBS/RS aisle is only responsible for either the vertical parts (the lifts) or the horizontal parts (the shuttles) in storage and retrieval services. The horizontal services are performed in parallel by multiple shuttles and are relatively decoupled from the vertical services, thus SBS/RS can potentially be more efficient and economical than many traditional S/R systems in high-speed demand environments – if designed and controlled properly. Moreover, in tier-to-tier SBS/RS the number of shuttles deployed to each aisle is a configuration decision, thus provides more flexibility in accommodating demand seasonality and reducing operational costs.

A typical SBS/RS-based warehouse system consists of multiple SBS/RS aisles that interface with the encompassing systems like the work (pick) stations and conveyor network. The aisles, workstations and conveyor network are subsystems of the larger warehouse system that need to be designed and configured with a holistic methodology in order to cost-effectively fulfill the changing demands and controlled and

coordinated in the operations so that to ensure efficient and sustainable performance of the storage and retrieval services. The design and configuration of SBS/RS requires precise and efficient performance estimation approaches for evaluating large numbers of design/configuration options. The development of operational control strategy involves clear identification of control decisions (storage assignment, task scheduling, etc.), and evaluation, integration and fine-tuning of control policies for different decisions.

The control decisions are highly correlated, while also largely affected by demand patterns as well as system design and configuration decisions. Recognizing the multi-stage nature of SBS/RS processes, we identify the critical design and control decision factors and illustrate the interdependencies between those factors in Figure 1, where important dependencies among those are denoted and highlighted.
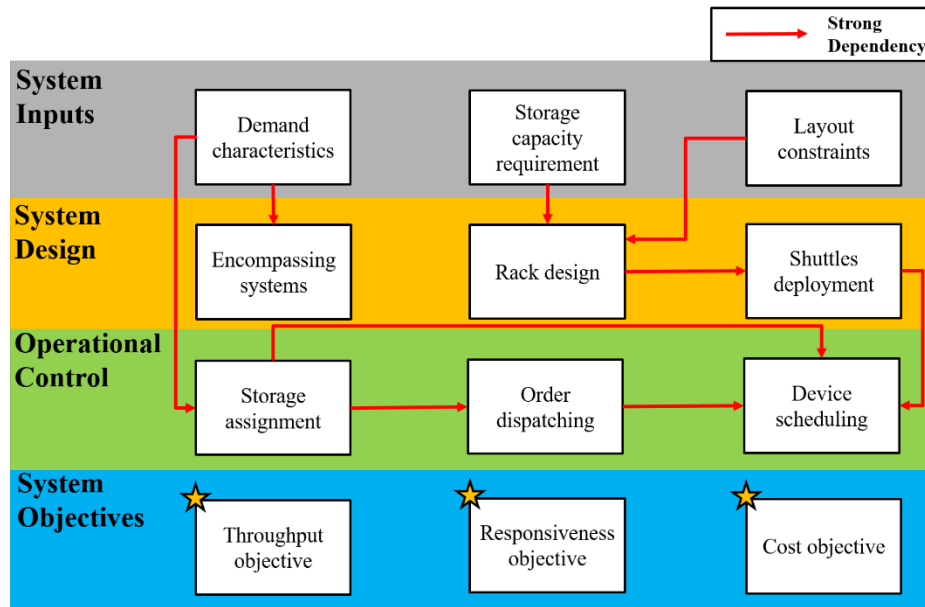
Figure 1: Key factors and decision-makings of SBS/RS-based warehouse design and control.

2   LITERATURE REVIEW

Ever since the introduction of the first aisle-captive crane-based Automated Storage and Retrieval System (AS/RS), continuous innovations based on the original design have been invented to better meet requirements under different circumstances. Autonomous Vehicle Storage and Retrieval Systems (AVS/RS) is one of the most preeminent innovations among all AS/RS variations. AVS/RSs are also called Multi-layer Shuttle Storage and Retrieval Systems. Ever since its first conceptualization by Malmborg (2002), AVS/RS has gained vast research interests from practitioners. An AVS/RS is characterized by horizontally operating vehicles sharing a fixed number of lifts for vertical movement (Malmborg, 2002). Compared with its traditional counterparts like crane-based automated storage and retrieval system (CBS/RS), AVS/RSs provide users more flexibility in system design and asset configuration by allowing the designer to change the number of vehicles operating in storage racks when demand changes.

Just like all innovative efforts made since the introduction of AS/RS, variations of AVS/RS to further improve system performance and reduce costs are studied. A **Shuttle-based Storage and Retrieval System (SBS/RS)** design applies a number of shuttles (vehicles) and two non-passing lifts – a storage lift and a retrieval lift – for each aisle. Different from the original AVS/RS, in SBS/RS both the lifts and shuttles are aisle-captive, thus no cross-aisle operations are performed. Also, unlike in the original AVS/RS design, vehicles in SBS/RS are not carried by the S/R lifts from/to I/O tiers. Instead, separate I/O buffers are installed for lift-shuttle interactions on each tier of each aisle. In traditional SBS/RS each tier is deployed with a dedicated shuttle (tier-captive), thus the number of shuttles is no longer configurable once the rack

dimensions are determined. Such designs are effective in situations where the demand scenarios are less uncertain. Another type of SBS/RS applies tier-to-tier techniques, where shuttles are transferred between tiers when needed by an aisle-captive shuttle lift. SBS/RS is also named as Multi-shuttle S/R System by many researchers (Carlo and Vis, 2012) and manufacturers.

Modeling and Simulation techniques are applied by many researchers to support AVS/RS design and control decision making. Ekren (2011) built a simulation model for an AVS/RS using commercial simulation software Arena. Marchet et al. (2013) investigated the main design trade-offs for a tier-captive AVS/RS using simulation, and developed a comprehensive design framework. Lerher et al. (2015) presented a simulation analysis for SBS/RS and explored the effects of various design assumptions. Tappia et al. (2017) developed queuing models which can handle both specialized and generic shuttles and both continuous and discrete lifts of multitier shuttle-based compact storage systems, and validated their models using simulation. Akpunar et al. (2017) applied simulation techniques to explore energy minimum AVS/RS warehouse design providing maximum utilization of resources in the system. Ekren (2020) developed a simulation-based experimental design for SBS/RS warehouse design by considering energy related performance metrics. Li et al. (2019) built a simulation model for a warehouse system consists of subsystems including multi-zone AVS/RS, pickup workstations, and conveyor network and studied the interactions between those subsystems to improve overall system efficiency and reduce blocking.

3   SIMULATION MODELLING

A data-driven and data-generated simulation model is built to support development of both the design and configuration methodology and operational control strategy of SBS/RS-based warehouse systems. To develop the simulation model, an iterative three-step methodology that includes Domain Modeling, Conceptual Modeling and Simulation Modeling is applied. Domain and Conceptual Models are important prerequisites for the simulation modeling approaches. The Domain model describes the problem domain and the conceptual model further describes the domain in language-independent simulation terms. As illustrated in Figure 2, system characteristics are identified and developed into simulation forms gradually in each step of the methodology, and reworks of the previous steps are performed whenever inconsistencies and discrepancies are observed. This iterative modeling methodology ensures the simulation model is a valid and acceptable abstraction of the practical SBS/RS-based warehouse systems to be analyzed and controlled under typical design and operational environments.
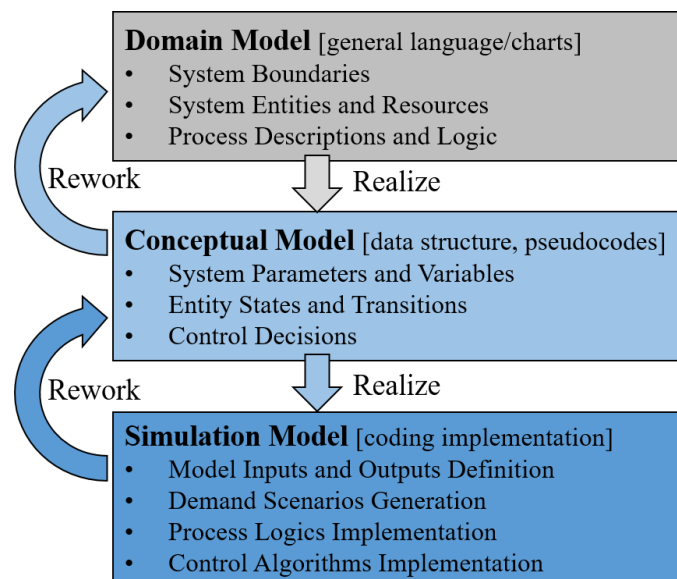

Domain Model [general language/charts]
- System Boundaries
- System Entities and Resources
- Process Descriptions and Logic

Rework | Realize

Conceptual Model [data structure, pseudocodes]
- System Parameters and Variables
- Entity States and Transitions
- Control Decisions

Rework | Realize

Simulation Model [coding implementation]
- Model Inputs and Outputs Definition
- Demand Scenarios Generation
- Process Logics Implementation
- Control Algorithms Implementation

Figure 2: The Iterative Domain-Conceptual-Simulation Modeling Methodology.

3.1   Modelling System Objects and Processes

Figure 3 shows how the devices within an SBS/RS serves storage tasks and retrieval tasks. The system illustrated here is 2-deep, which means there are two storage rows in the z-axis on both sides of the aisle. Shuttles (autonomous vehicles) are responsible for horizontal movement for both storage tasks and retrieval tasks. A shuttle travels on rails on each tier, accesses storage locations of both depths using its arms, and each time carries no more than one tote. Two tote lifts, namely the storage lift and retrieval lift, are elevators responsible for vertical movement for storage tasks and retrieval tasks, respectively. Each tote lift is a continuous elevator so that it may carry more than one tote within a tour. Moreover, as the total number of shuttles is usually less than number of tiers, there is a dedicated shuttle lift responsible for transferring shuttles between tiers when needed.

The shuttle and shuttle lift operations are illustrated in Figure 4. The input/output buffer conveyors on the left-most side of each tier are temporary stacking locations between shuttle (horizontal) services and tote lift (vertical) services. In a retrieval task, the service shuttle (shuttle.1) moves from its current column to the column of the tote's slot, loads the tote, then moves to the output buffer on the tier, and finally unloads the tote to the buffer. The shuttle is then released, and the tote is waiting for the next phase of retrieval service provided by the retrieval lift. In a storage task, the tote to be stored is delivered to the input buffer conveyor through the first phase of storage service provided by the storage lift. The service shuttle (shuttle.2) then moves from its current column to the input buffer, loads the tote, then moves to the column of the tote's target slot, and finally unloads the tote to slot. The shuttle is then released. In addition, for 2-deep aisles, a retrieval task from a 2-deep slot could be blocked by a tote stored at the slot's neighboring 1-deep slot – in such cases, relocation of the blocker tote needs to be performed by the shuttle.
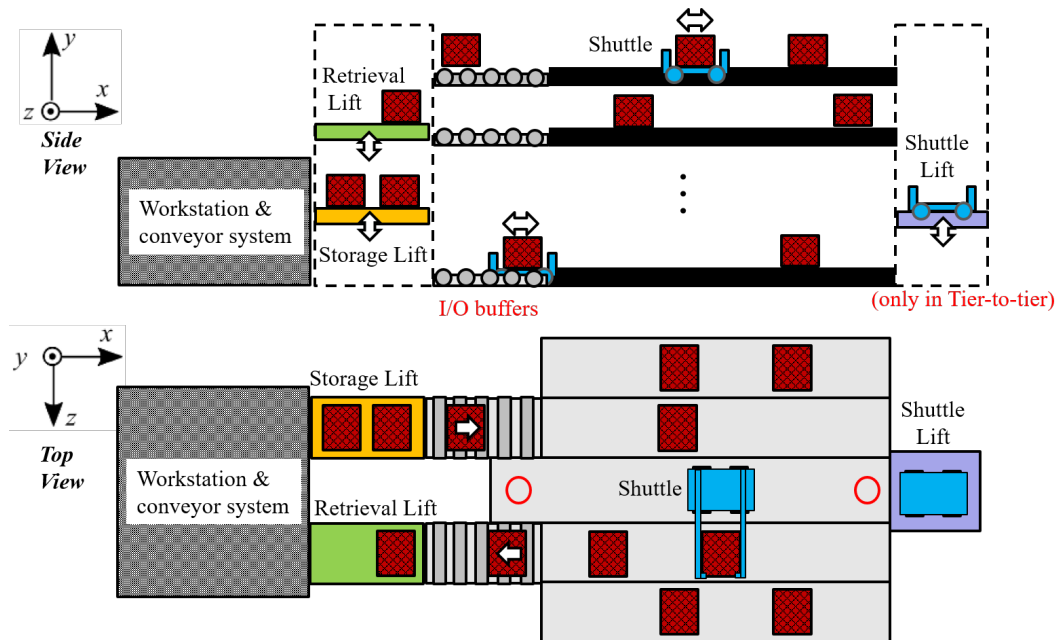

Figure 3: Operations within a single aisle of a tier-to-tier SBS/RS.

In cases where there is no available shuttle to serve a storage task to a target tier or retrieval task from a target tier, shuttle tier-transfer operations must be conducted. First, a shuttle (shuttle.3) from another tier is selected and moves from its current column to transfer station at the right-most side of the tier. Then, the shuttle lift moves from its current tier to the shuttle's tier, load the shuttle, then carries the shuttle to the target tier of the task, and finally unload the shuttle at the transfer station on the target tier. The shuttle lift is then released, and the shuttle proceed to serve the task.
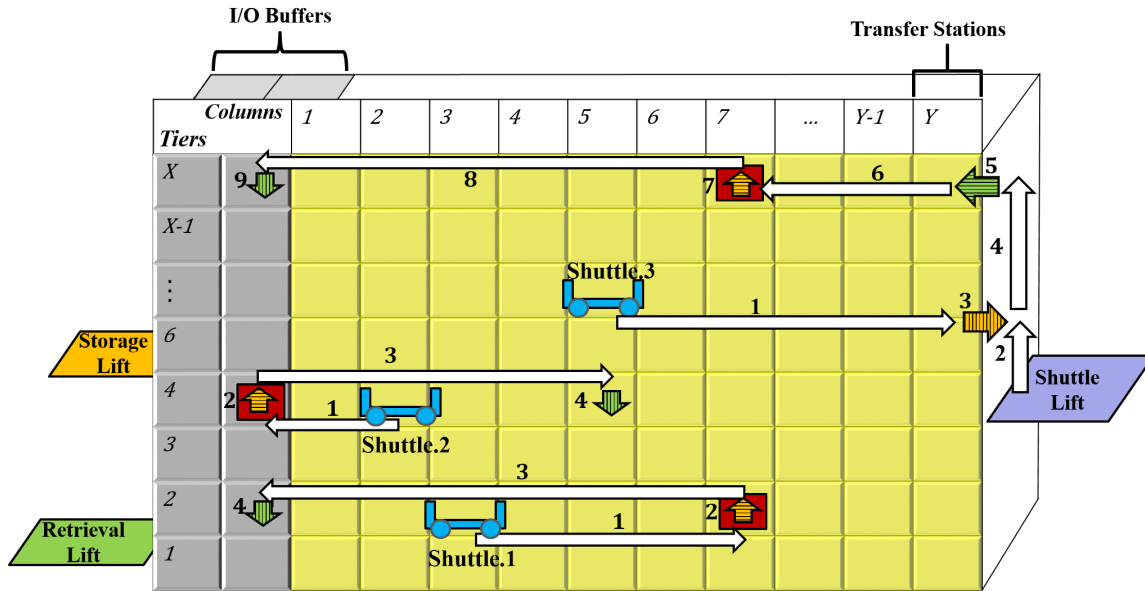
Figure 4: Shuttle Operations Illustration of a tier-to-tier SBS/RS.

Operations of the storage lift and retrieval lift are illustrated in Figure 5. The tote lifts can be either 1-capacity or multi-capacity depending on the technology applied – for the latter, the lifts can carry more than one tote at a time in each tour. In a storage task, the storage lift moves from its current tier to I/O floor to load the totes delivered by encompassing systems (e.g., conveyor system which delivers storage totes to the SBS/RS). Next, the lift moves to the target tiers of each storage totes, and finally unload the tote to the target tier's input buffer. In a retrieval task, the retrieval lift moves from its current tier to the tier of each retrieval tote and loads it, then moves to the I/O floor and finally unloads the tote.
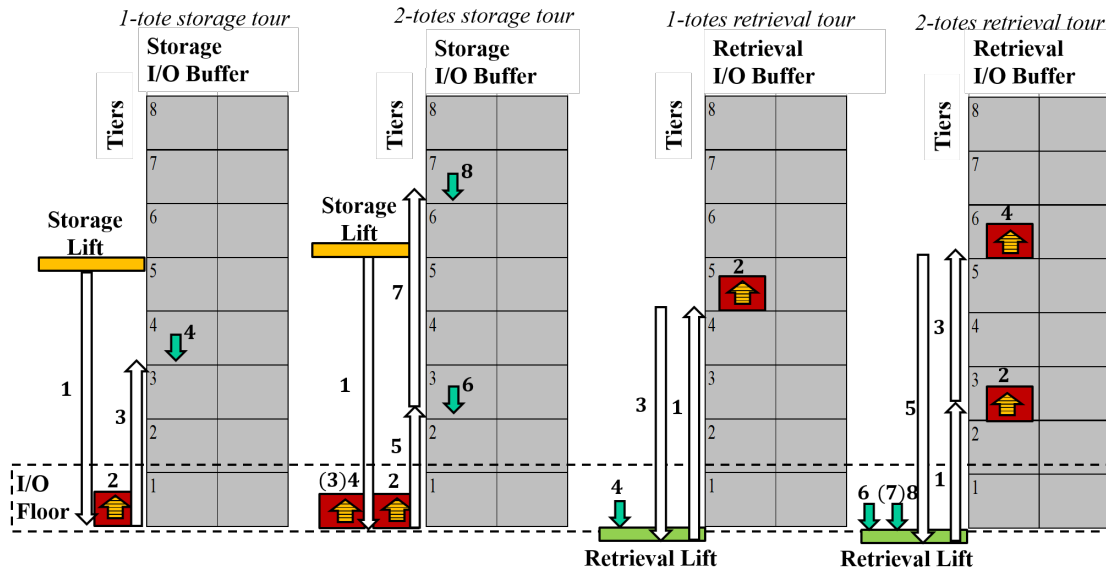

Figure 5: Tote Lift Operations Illustration of a tier-to-tier SBS/RS.

The simulation model is auto generated with predefined input data of design parameters including the numbers of aisles, tiers, columns, depths, shuttles deployed, etc., as well as physical parameters including rack dimensions, device velocities and accelerations, L/U(load/unload) times, etc. Each *aisle* of the SBS/RS is modeled as an individual service unit that contains a set of S/R devices, a rack storage area which is a set of *slots* indicated by (x, y, z) coordinates, and the roller-conveyor *input/output buffers* on different tiers. Discrete Event Simulation (DES) techniques are selected as the main methodology for developing the simulation model, while some Agent-Based Simulation (ABS) techniques are also applied for modeling the low-level device-task interactions. The aisle's S/R devices including *shuttles*, *storage lift*, *retrieval lift* and *shuttle lift* are modeled as agents each has specified logics for providing storage and retrieval services. On the other hand, the task lifecycles and device service times are simulated under the DES framework. Generally speaking, the service times of all devices can be described in two aspects: the times needed for L/U operations, and the rectilinear travel times. Given a service process described as a set of movement, load and unload commands, device service times are simulated deterministically under the DES framework: the devices' L/U times are modeled as constant parameters, and the rectilinear travel time between every two locations i and j (either horizontal or vertical) with distance l are computed precisely given the device's velocity v, acceleration a and deceleration d as follows:

$$\tau_{i,j} = \begin{cases} \sqrt{2l\left(\dfrac{1}{a+\dfrac{a^2}{d}} + \dfrac{1}{d+\dfrac{d^2}{a}}\right)}, & if \ l < 0.5v^2\left(\dfrac{1}{a}+\dfrac{1}{d}\right) \\ \dfrac{v}{a} + \dfrac{l - 0.5v^2\left(\dfrac{1}{a}+\dfrac{1}{d}\right)}{v} + \dfrac{v}{d}, & Otherwise \end{cases} \tag{1}$$

The device travel times of all feasible paths (either horizontal or vertical) are pre-computed based on the input data during model generation.

3.2 Modelling Demand Scenarios

Totes are defined as the basic entities in the simulation model, either stored in slots or transported by the S/R devices. The initial tote inventories in the aisles' rack storage areas are either auto-generated according to rack utilization parameter settings, or predefined in the input data. *Tasks* represents the minimum demand entities describing the information required for the S/R devices to provide services and the corresponding totes. A task can either be a *storage* task or a *retrieval* task, both require services from more than one S/R device. Moreover, under control assumptions where SKU-level characteristics are considered, SKU information is modeled as parameters/variables related to totes and tasks.

Demand scenarios are defined as the task arrival patterns to the aisles, either described by stochastic task arrival process based on a user-configurable order structure and SKU-level characteristics/parameters, or described by task sets and inventory information predefined in the input data. In the former case, the arrival processes of storage tasks and retrieval tasks to each aisle are defined in terms of inter-arrival time (IAT) distributions. The IAT distributions are defined as general random, non-negative distributions, each described by distribution mean (μ) and standard deviation (σ). When the focus is analyzing the systems' steady-state performances, the arrival rates of storage tasks and retrieval tasks must be equal, thus there is $\mu_S = \mu_R = 1/\lambda$ in which λ is the average task arrival rate for both task types ($\lambda = \lambda_S = \lambda_R$). On the other hand, there is not necessarily $\sigma_S = \sigma_R$ because σ_S and σ_R are measuring the variance of two different processes at the upstream of the system: σ_S is corresponding to the patterns that the storage totes are delivered to the aisles (e.g. from conveyor networks or/and docking areas), while σ_R is corresponding to the patterns that retrieval requests are released to the aisles (e.g. by higher-level systems like MRP). In this research, we use lognormal distributions to approximate the general distributions of the IATs, because the lognormal distribution can be described by the mean and standard deviation to flexibly describe different

variances of storage and retrieval IATs, and only gives positive values. In the simulation model, each of the two general distributions are approximated as an individual lognormal distribution $Lognormal(\mu_N, \sigma_N)$, where μ_N, σ_N are the mean and standard deviation of the included normal distribution, computed given the objective μ, σ as follows:

$$\mu_N = 2\ln(\mu) - 0.5\ln(\sigma^2 + \mu^2), \quad \sigma_N = \sqrt{-2\ln(\mu) + \ln(\sigma^2 + \mu^2)} \tag{2}$$

In practical operations, correlations exist between the arrivals of storage tasks and retrieval tasks. However, such correlations are very difficult to identify precisely because they are usually originated both from the nature of the SBS/RSs' application environments (e.g., those correlation could be very different between E-commerce applications and manufacturing applications), and from the configurations and performances of the SBS/RSs' upstream systems (e.g., the conveyor networks, MRP). Three alternative solutions are proposed and implemented in the simulation model to address such complexity:

1) No explicit modeling of SKUs, while approximating the storage-retrieval correlation by controlling the numbers of storages and retrievals within specific time windows;
2) Model SKUs explicitly, and model the demand and replenishment patterns as random processes based on SKU types;
3) For manufacturing environment applications. Based on 2, model manufacturing orders as sets of retrieval tasks with precedence constraints. Model the additional pickup and return-to-stock patterns upstream and downstream of the SBS/RS as random processes for each order.

In this research, we primarily focus on the first solution.

3.3   Simulation Realization

The operations in the SBS/RS including device movements, acceleration and loads/unloads, as well as the dynamics in task, tote and SKU information, etc., are simulated precisely using a hybrid simulation methodology based on DES and ABS techniques. The simulation models are implemented in AnyLogic (Grigoryev 2015), which is a commercial multimethod simulation modeling tool. Different technology options including tier-captive/tier-to-tier configurations, multi-capacity tote lifts, multi-deep racks, as well as design options for encompassing systems, are implemented. 3D animations and various output statistics are developed and used to facilitate the analysis of the systems' dynamics as well as the verification of the control approaches (Figure 6).
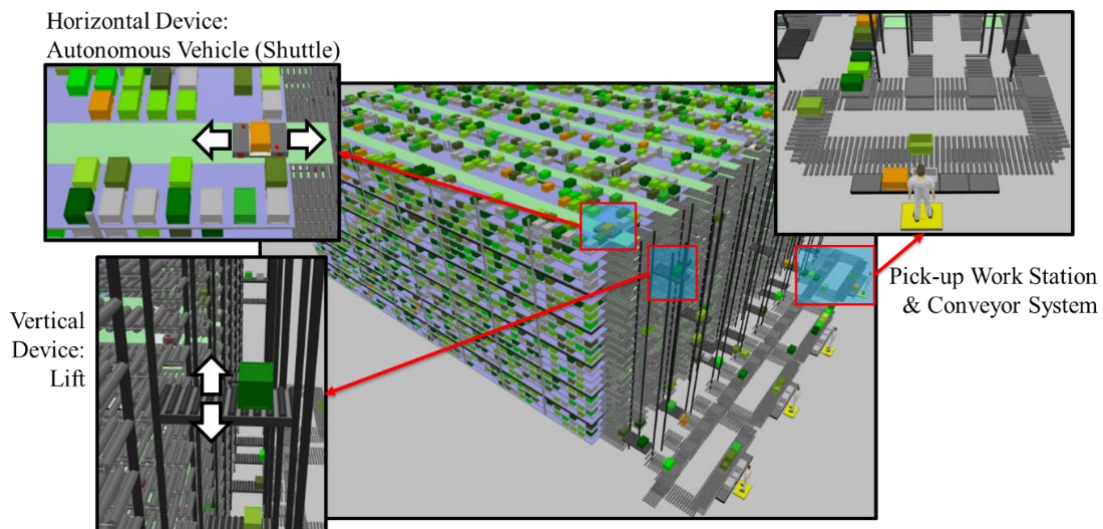

Figure 6: SBS/RS-based warehouse system simulation model built with AnyLogic.

4   IMPLEMENTATION OF OPERATIONAL CONTROL ALGORITHMS

Operational control decisions involving storage assignment as well as task scheduling for different devices, are identified in Table 1 and implemented in the simulation model as illustrated in Figure 7. Generally speaking, all these control decisions can be interpreted as "select one from multiple candidates". Those control decisions can be made either based on bottom-up approaches like dynamic dispatching rules, or through top-down approaches like mathematical programming – or even some heuristics that combine the advantages of both. Moreover, for each control decision, various alternative and user-configurable control approaches are identified and implemented in the simulation model, as listed in Table 1.

Table 1: Operational control decisions in an SBS/RS aisle

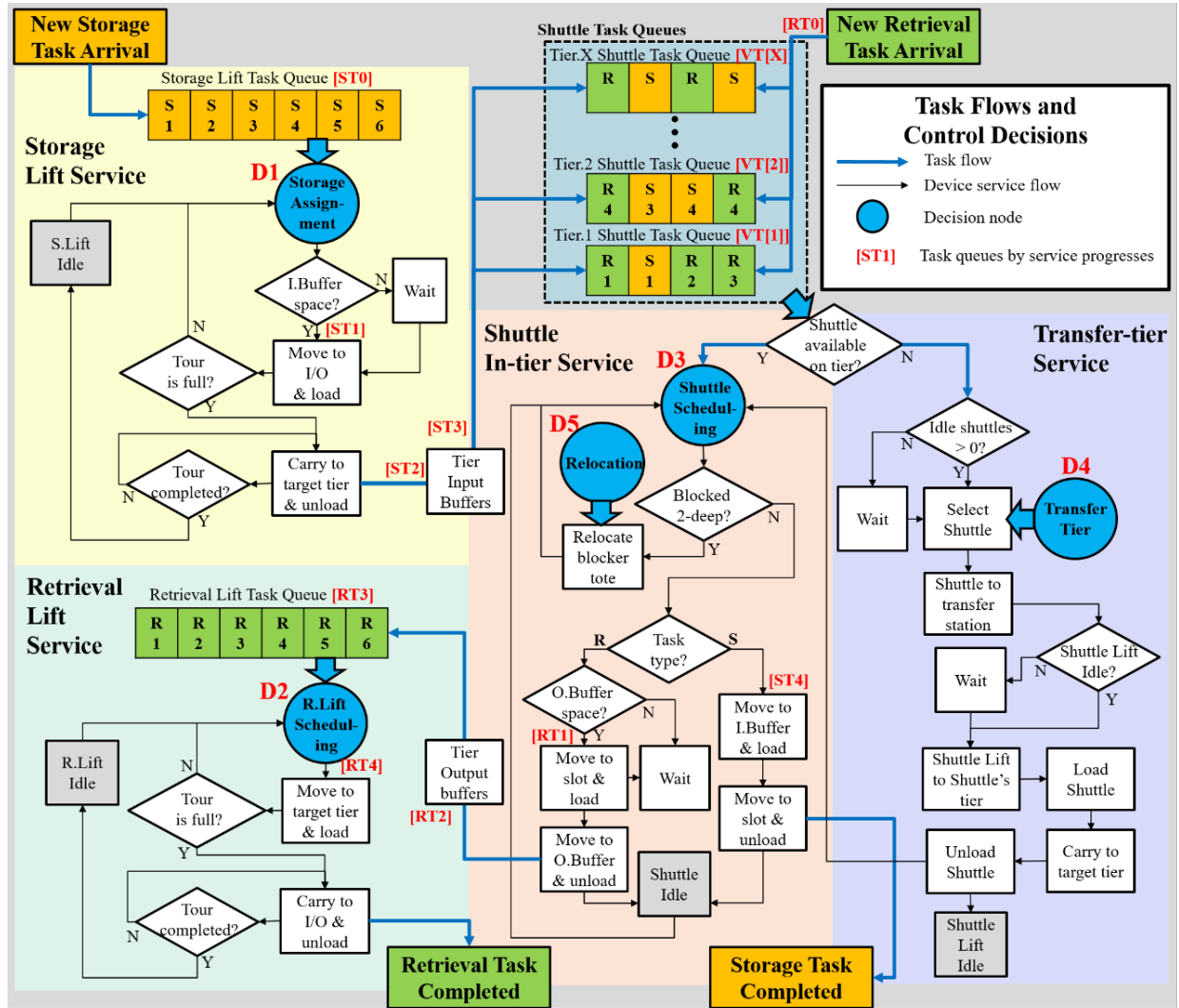| Control Decision	Selection Candidates	Alternative Approach Examples

D1:
Storage
Assignment
	Available {**slots**} in the aisle
	[select one slot for each storage task arrived to the aisle]
		• Pure Random Storage (PRS)
		• Closest Open Location (COL)
		  • Consider horizontal distances only
		  • Consider both horizontal and vertical distances
		  • Prioritize 2-deep slots
		• By number of available slots on tiers (largest)
		• By input buffer sizes of target tiers (smallest)
		• By SKU characteristics
		  • Predetermined zoning by SKU turn-over rates
		  • By correlations of SKU-types

D2: Retrieval Lift Scheduling	Retrieval {**tasks**} that completed shuttle services and unloaded to the output buffers [select one task as the next task for retrieval lift service]	• First Come First Serve (FCFS) • Closest to R.Lift's current location • Earliest Due Date (EDD) • By output buffer sizes of target tiers (largest)
D3: Shuttle Scheduling	Storage {**tasks**} that completed storage lift services and unloaded to the input buffers; Retrieval {**tasks**} arrived to the aisle [select one task (either type) as the next task for shuttle service]	• First Come First Serve (FCFS) • Closest to shuttle's current location • Earliest Due Date (EDD) • Dual Cycle Interleaving (DC) • Makespan Minimization Heuristics • A* Search Algorithm
D4: Relocation (for 2-deep racks)	Available {**slots**} on the tier of each retrieval task arrived but blocked by a tote (blocker) in the neighboring slot [select one slot for each blocker]	(Similar with D1 except that the search scope is within one tier)
D5: Tier-transfer (for tier-to-tier systems)	1. {**tiers**} that have shuttle tasks but without shuttles 2. {**shuttles**} that are idle [select one tier and one shuttle for each transfer-service]	• By number of tasks on tiers (largest) • By expected shuttle travel times (smallest) • Resource Allocation Heuristics • $P||C_{max}$ Algorithm

Figure 7: Implementation of the operational control decision in the simulation model.

5   VERIFICATION AND VALIDATION

Verification and validation (V&V) of the simulation model are performed using the aforementioned iterative Domain-Conceptual-Simulation modelling methodology. The verification of the simulation model is primarily based on various system performance statistics (either real-time or tally) collected by the model (Figure 8). Other model verification approaches, including code walk-throughs, visual verification using the model animations, and cross-verification with the queuing-based analytical model, where also performed continuously throughout the research. In addition, during the 18-month research project with our industry partner, the simulation model is continuously validated by our sponsors who manufacture SBS/RS products and provide automated warehousing solutions to their customers in various industries. The validation approaches in this research are primarily can be described in three aspects:

1) **System parameters**. The physical parameters of the racks (both 1-deep and 2-deep) are valid presentations of the sponsors' standard design criteria. Devices' velocity, acceleration/deceleration and L/U time parameters are determined based on the actual device performances tested by the sponsors.

Miscellaneous design factors, for examples the existence of maintenance floors (which makes the vertical distances between tiers non-uniform), and devices' response delays from the Warehouse Control System, and buffer conveyor capacities and speeds, are also considered in the simulation model according to the needs of the sponsors.

2) **Demand formulation**. Although practical demand information from the sponsors' customers is not accessible due to confidentiality reasons, our formulation of S/R tasks and IAT distributions are validated by the sponsors as acceptable approximations of the practical operational environments. Moreover, the simulation model can also take deterministic tasks (deterministic arrival times, and either predetermined storage assignment or not) described in spreadsheet format as model inputs to facilitate V&V.

3) **Device control**. The general service processes and the control decisions are validated by the sponsors. The control algorithms are verified and validated through systematic development approaches based on both top-down approaches and bottom-up approaches. Besides the five control decisions for scheduling and storage assignment identified, other control rules (e.g., device dwelling policies) are also implemented as options in simulation although they are not the primary focus of this research.
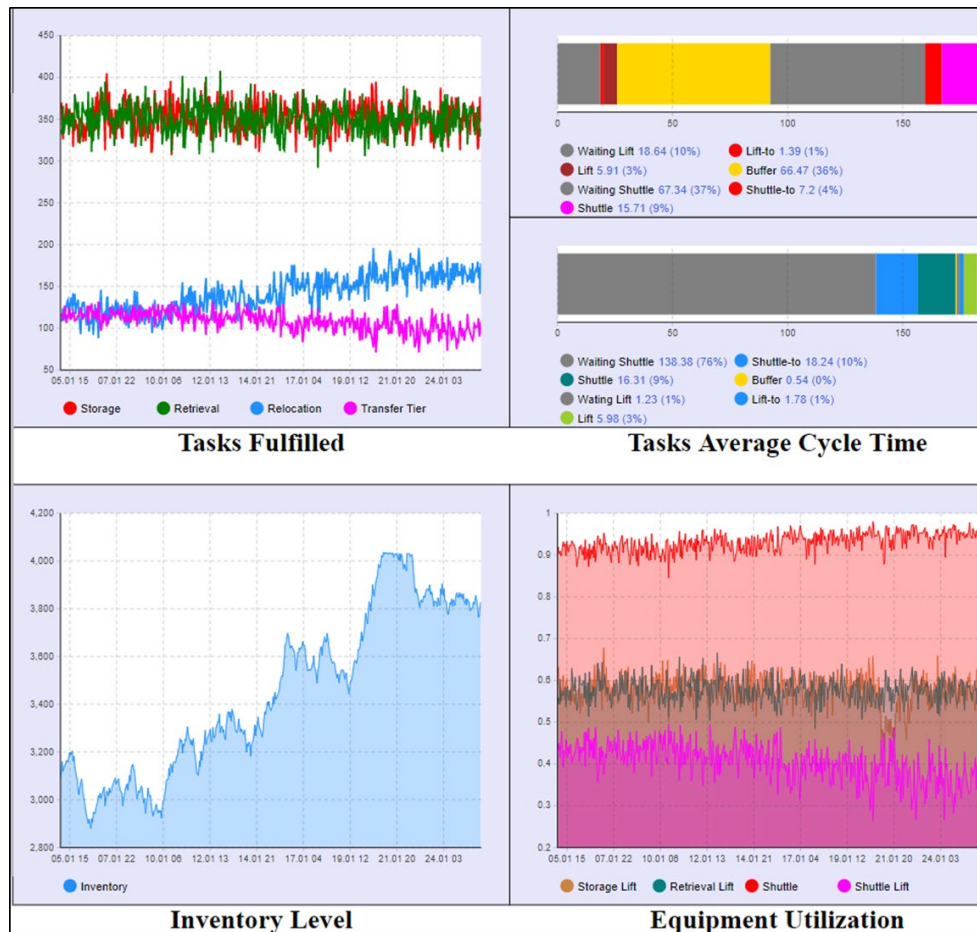

Figure 8: System performance statistics in the simulation model.

It is noticeable that the model validation is an on-going task that accommodates the future requirements proposed by the sponsors and/or decision makers. For example, industrial users can continue this process incorporating their own proprietary/confidential data and design/configuration criteria, and explore design and control methodologies for their own business in further research.

6   SIMULATION-BASED DESIGN AND CONTROL METHODOLOGY

According to a survey conducted by Smith (2003), the application of simulation technology in manufacturing systems can be classified into three classes: 1) for system design that involves long-term decisions and the analysis of design alternatives; 2) for system operations that involve short-term decisions including operations planning and scheduling, real-time control, operating policies, and performance analysis; and 3) simulation language/software package development. The simulation model in this research is primarily developed to support the first two classes: the system design decisions (conceptual design) and the system operation decisions (control strategy development) of SBS/RS warehouses, as illustrated in Figure 9. On the other hand, although the simulation model is developed on a specific commercial simulation software (AnyLogic), the modeling approaches applied here are generalized and most of the model logic components are coded in the Java language. Thus, the simulation techniques here are considered as compatible with different simulation platforms, feasible for software packaging, and potentially expandable to similar warehousing systems of larger scopes or/and applying different AS/R technologies.
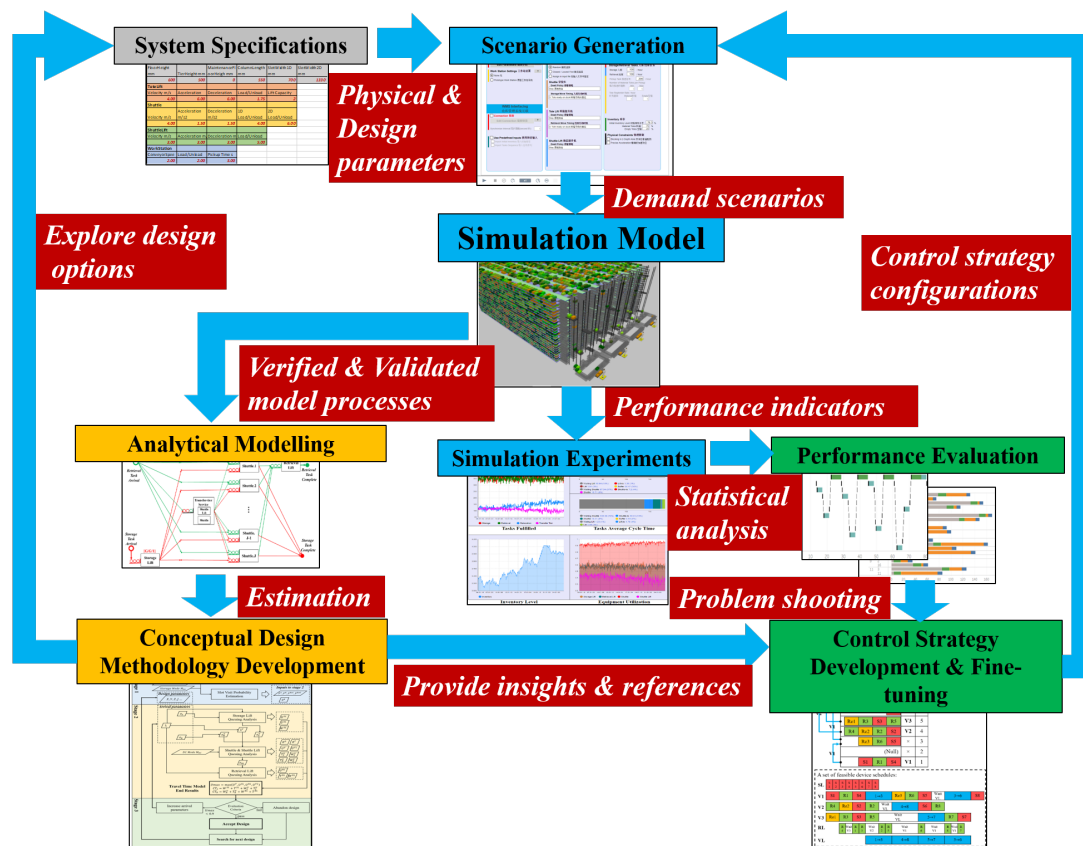

Figure 9: Using the Simulation Model for Conceptual Design and Control Strategy Development.

7   CONCLUSIONS

The generic, data-generated simulation model was developed according to an iterative Domain Modeling, Conceptual Modeling and Simulation Modeling methodology. System objects and service processes, demand scenarios, as well as control decisions are modeled, verified and validated. Demand scenarios are modeled based on random inter-arrival-time distributions of storage and retrieval tasks, and alternative

modeling solutions are proposed to handle the storage-retrieval correlations and SKU-level characteristics. Five types of control decisions – storage assignment, retrieval lift scheduling, shuttles in-tier scheduling, relocation, and tier-transfer – are identified. Multiple alternative control approaches are developed for each control decision and implemented in the simulation model. The simulation model is expected to support both the development of conceptual design methodology and the development of operational control strategies of SBS/RS warehouses, respectively. Finally, the simulation techniques applied are viewed as potentially expandable to similar warehousing systems of larger scopes or/and applying different AS/R technologies.

This paper is developed based on the doctoral dissertation of the author Donghuang Li, Auburn University. Simulation-based design configuration and control strategy development are explored in depth in the dissertation work. Please refer to https://etd.auburn.edu/handle/10415/8130 if interested.

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