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DECISION SUPPORT MODEL TO EVALUATE COMPLEX OVERHEAD CRANE SCHEDULES

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ABSTRACT

Boeing Commercial Airplanes produces four twin-aisle airplane models at its Everett, Washington production facility—the largest building by volume in the world. Efficient and effective material handling of large airplane substructures is critical to maintain production rates, and the Everett facility employs two interconnected systems of overhead cranes to move airplane sections through the factory. The crane scheduling team needed a tool to evaluate current and proposed crane schedules for feasibility, rate capability, and potential bottlenecks. Boeing Research and Technology partnered with Simio LLC to develop a simulation model of the crane network that would execute and evaluate a series of crane moves. The model employs both discrete event and agent-based paradigms to model the complex system and to allow for highly configurable initial states. This approach allows for rapid schedule evaluation, non-recurring planning, and real-time system modeling. In this paper we present the system, the model, and results.

1 INTRODUCTION

Overhead cranes are a common method for material management in large scale manufacturing and assembly processes. An overhead crane system offers flexibility in addition to potential reduction in floor space required for tooling and equipment. The Boeing Company uses overhead cranes in its Everett, Washington final assembly plant where all models of its twin-aisle aircraft are built. This facility (the largest building in the world by volume) has nearly 100% crane coverage of manufacturing floor space. Boeing uses the latest under-hung crane technology which allows a single cab to move a load not only between adjacent bays, but also to different adjacent buildings.

Scheduling of material handling systems is a well-studied topic (Zhang and Rose 2013). Efficient material management scheduling and execution can create a competitive advantage for a manufacturer, and enable increased capacity, decreased flow times, and increased resource utilization (Cerda, 1995). Finding optimal solutions to scheduling problems is generally a difficult proposition as they are combinatorial optimization and often strongly NP-hard (Demeulemeester and Herroelen 2002). The crane scheduling problem is no exception – it is an NP-hard problem (Chang-bo et al. 2010) Therefore simulation is a tool well-suited to study of complex material management systems.

This research is concerned with modeling and simulating a complex overhead crane system. Previous researchers have developed simulation based tools for scheduling and analysis of material handling systems. There is a fair amount of research that considers cranes in container terminals. Lim et at. (2002) developed a tabu search based crane scheduling system for container ports. Guo et al. (2008) developed a yard crane dispatching tool based on real time data driven simulation for container terminals. However, this research considers a manufacturing setting for which it is difficult to apply the results from scheduling in container terminals.

There is some research focused on overhead crane scheduling in manufacturing plants. Ge and Yih (1995) consider a crane scheduling problem with time windows in a flow-shop production system. They develop an optimization-based scheduling heuristic and employ simulation to demonstrate that the algorithm yields good results. Matsuo et al. (1991) consider a single crane scheduling system in a Computer Integrated Manufacturing environment. They demonstrate that cyclic scheduling yields good results for simple problems, that a network flow approach yields good results in multi-product systems, and finally that a heuristic for sequencing product types in a cycle minimizes overall cycle time. Chang-bo et al. (2010) developed a simulation model to solve the NP-hard problem of crane scheduling by developing a simulation method for crane scheduling in a workshop of steel making based on a multi agent system (MAS). Zhang and Rose (2013) develop a simulation-based optimization algorithm to solve the integrated production scheduling-crane scheduling problem.

Our focus is on modeling and evaluation of a significantly more complicated system than those typically found in the literature. The primary novelty derives from the physical complexity of the underlying system, as well as the issues involved with modeling such a system and implementing a decision support tool. Most the systems in the manufacturing literature are relatively simple, for example, Aron et al. (2008) consider a system with two hoists on a single track, while we consider a system in which cabs can move between multiple tracks. Scheduling is complicated due to the multiple sets of decisions (sequencing, routing, timing, and allocation), and simulation is complicated due to the nature of the system.

We are concerned primarily with modeling and use of the model for schedule evaluation. Simpler systems are more amenable to schedule optimization, but that is one of the salient features of the problem – approaches developed for simpler systems do not always scale efficiently. There are many manufacturing systems employing overhead cranes in the world, and the approach, while developed in the context of a Boeing production facility, is more broadly applicable.

The scheduling itself is outside the scope of the system (Figure 1). Like Guo et al. (2008), our research focuses on the integration of real time data in a decision support system. In this paper, we discuss the aims of the simulation project, the system under study, the simulation model, and the results.

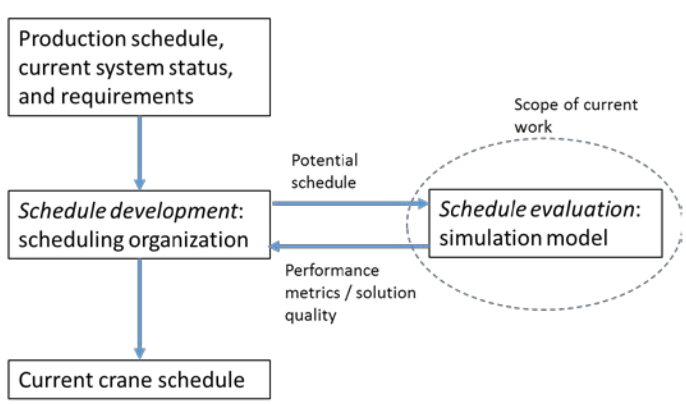


Figure 1: Schedule workflow and study scope

2 INVESTIGATION AIMS

The aim of this project is to provide crane schedulers with a flexible, configurable tool for evaluating crane schedules. The first task to accomplish this aim was to build a simulation model that would allow for quantitative and qualitative evaluation of a given schedule. Requirements included a spreadsheet-based input format, arbitrary pickup and drop-off locations for an arbitrary set of moves, arbitrary initialization of crane resources, and 3D visualizations of crane movements. Secondary tasks included an evaluation of schedule fitness, the ability to have control over specific move routing, and the ability to combine schedules from multiple production lines that use the overhead crane system simultaneously. Due to the complexity of the physical system, this project does not make an attempt to generate move schedules or to optimize move sequences. This restriction is also due to a lack of system-wide job precedence data across multiple product lines.

3 SYSTEM DESCRIPTION

3.1 Components of overhead material handling system

The components of the overhead material handling system and their salient properties are diagramed in Figure 1. The system consists of multiple cranes that have a one-to-one association with a cab. For the purposes of this paper, the terms “cab” and “crane” are synonymous. A crane operator sits in the cab and actuates a lift to move objects. The cab travels on bridges that are oriented east to west. The bridges are contained in a bay that is two or three bridges wide, and the bridges can move north to south within the bay. Additionally, each bay has a series of two or three bridges. Cabs can lock bridges together creating one larger bridge that moves as a unit in the bay. Such a system is highly complex with a very large number of configurations and states. This complexity was a primary driver for a model-based approach for schedule evaluation. The system as modeled contains 16 bays, one transportation aisle connecting the bays, 45 bridges, and 9 cabs. The components and properties are described in detail in section 4.3.

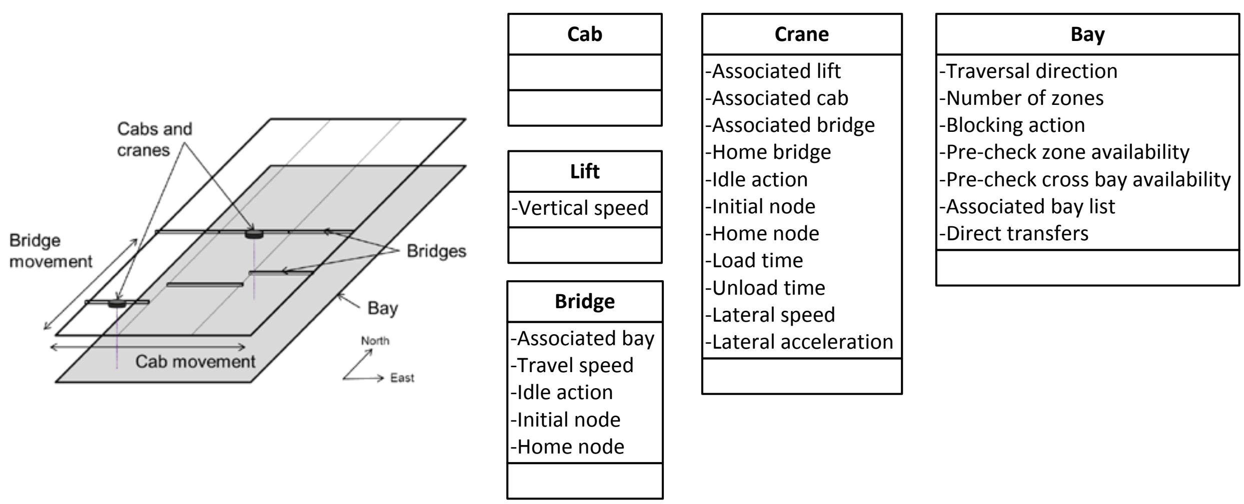


Figure 2: System components and salient properties.

3.2 System Complexity

Complicating the schedule evaluation problem is the complexity of the system under study. The physical layout of the manufacturing plant consists of 16 bays connected by a primary transportation aisle and inter-bay transfer points. An example schematic showing the relationship of bays, bridges, cabs, and transportation aisle is shown in Figure 3. Further, the material handling system supports two independent product lines that have spatial overlap throughout the factory. These product line schedules are managed independently, and it is the crane scheduler's responsibility to determine a schedule that meets both product's schedule requirements. These independent schedules are subject to high degrees of variation due to different build plans, different production rates and rate changes, and production delays. In addition to crane system resources, the products share certain key production resources such as paint booths.

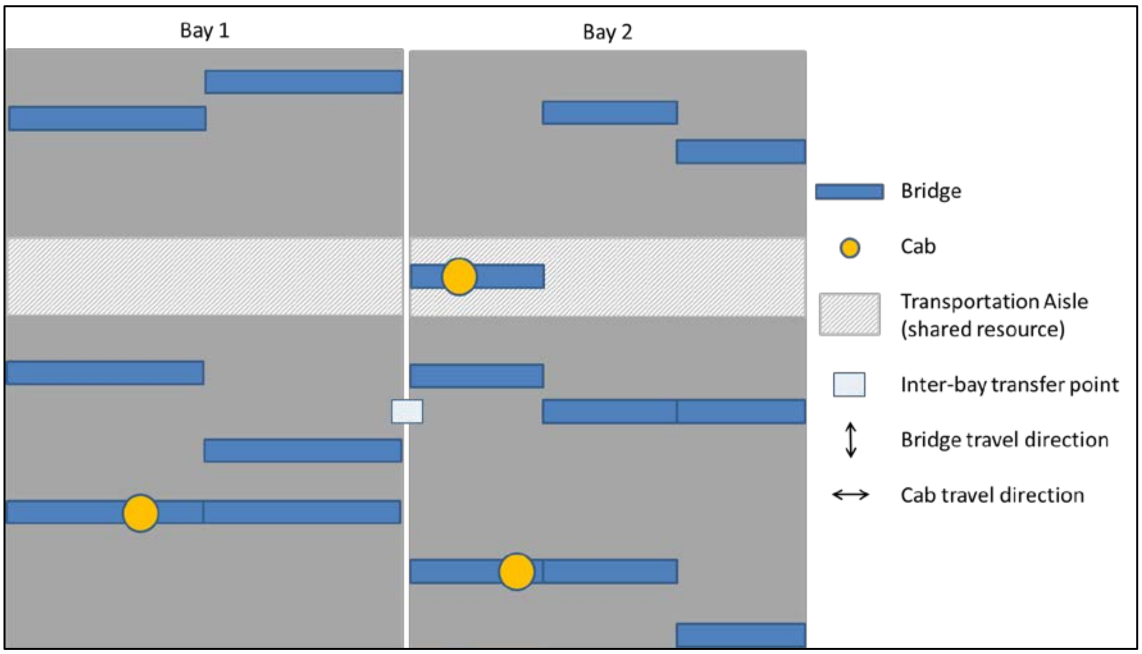


Figure 3: Example schematic showing the complexity of the system.

The need for a decision support tool for schedule evaluation was motivated by this complex, interdependent production system. Each product line is requesting its own schedule independent of other activities in the factory, and the schedulers needed a tool to evaluate integrated schedule fitness.

4 SIMULATION MODEL

4.1 Implementation

The requirements of the investigation suggested that a discrete event simulation model with agent-based capability and native 3D modeling was required. Specifically, the manufacturing environment was best modeled in a discrete-event paradigm, where transport requests are events scheduled on an event calendar and states are non-continuous. The crane assembly is best represented by a collection of agents that communicate with other agents in the collection, with other collections, and with other system agents such as bridges. This allows for autonomous decision making to respond to and execute move requests. It also allows for continuous state variables—for example, crane acceleration is important to model accurately—and free space movement.

The investigators chose the Simio software package because of its ability to meet these specific requirements, in addition to its flexible object-oriented approach (Pegden 2008). Simio has been used successfully in a variety of manufacturing applications. Mandalaki and Manesis (2013) used Simio for the three-dimensional modelling of the new port of Patras city (Greece) in Simio.

4.2 Data Collection and Preparation

Data collection and preparation was key to the success of this study. The initial data requirements were for only key locations throughout the facility to be included in the model; however, this approach lacked flexibility for general schedule evaluation. A grid applied over the factory layout provided the necessary structure and flexibility for scheduling moves to and from arbitrary locations with the factory. Each grid point is represented by a node object in the simulation model; these nodes are not connected to a network. The material moves are defined as arrivals of material at one node that need to be moved to another node . Additional data was collected to define the bays and zones that determine spatial constraints and deadlocking detection and avoidance.

Schedule data to be evaluated is the primary input data for a simulation run. This data also required preparation. The schedulers currently use a non-standard and inconsistent format for scheduling moves. This format was modified to allow for automated processing and importing into the simulation model. The format includes a validated and enforced structure for move times, locations, and required resources. This data is then transformed into input for the simulation using standard spreadsheet data manipulations. This workflow allows for minimal workflow changes for the crane schedulers while enabling full flexibility for data input into the simulation model. Additionally, there are optional data fields that allow significant configuration of the initial state of the model. Real time data is used for model initialization. This includes bridge location and cab-to-bridge assignments. By utilizing this capability, the model can easily be used for evaluation of schedules with the current or expected state of the factory captured. The model has data corresponding to moves (indexed by *i*), bridges (indexed by *j*), and cabs (indexed by *k*). Table 1 describes the data required for a schedule of *M* moves. Table 2 details the initialization data required for the model.

Table 1: Schedule data

Data	Description	Type
m_i	Move identifier for ith move	Alphanumeric
t_i^{start}	Scheduled move start time of ith move	Datetime
loc_i^{start}	Originating location of ith move	Node identifier
loc_i^{dest}	Destination location of ith move	Node identifier
$loadtime_i$	Load time for ith move	Time
$unloadtime_i$	Unload time for ith move	Time
$cabs_i$	Ordered list of preferred cabs for ith move	Ordered list
$HoldLeftBridge_i$	Hold bridge to the left of the destination bridge?	Boolean
$HoldRightBridge_i$	Hold bridge to the right of the destination bridge?	Boolean
$BypassTransportationAisle_i$	Do not use transportation aisle for inter-bay moves?	Boolean

Table 2: Initialization data

Data	Description	Type
Loc_j^{init}	Initial location of j^{th} bridge	Node identifier
Loc_j^{home}	Home location of j^{th} bridge	Node identifier
$Bridge_k^{init}$	Initial bridge of k^{th} cab	Bridge identifier
$Bridge_k^{home}$	Home bridge of k^{th} cab	Bridge identifier

There are over 700 locations (node objects) in the model. To simplify the definitions of the locations, a custom program was used to define, position, and place the node objects in the model using a spreadsheet as input. Roughly 15 bays, 50 bridges and 10 crane assemblies were also imported into the model from spreadsheet-based input data. The bays are 400 to 500 meters in length (north to south) and 50 to 75 meters in width (east to west). Typical schedules for evaluation consist of 400 to 500 moves over the course of five manufacturing days.

4.3 Crane Library

The model was built in Simio using a custom developed crane library that is now available for general use. The crane library enables the modeling of crane movements within a manufacturing facility using agent-based objects. The library is setup to allow the movements of multiple cranes within the same area without conflicting with one another.

The crane library consists of objects representing bays, bridges, lifts, cabs and end effectors. These agent objects are combined together to model multiple cranes moving in a bay and across bays. A crane movement occurs by first rising up its end effector from the pickup location node to a specified travel height, traveling laterally at that height and then lowering down to the specified drop-off location node. All travel is done through free space without the need to explicitly draw a network. The crane library also fully supports independent acceleration/deceleration and the ability for one crane to cause another blocking crane to move out of the way.

The key object in the library is the end effector (or carrier) which represents the device picking up and moving a material. The end effector in turn communicates with its associated lift, cab and bridge to move across the bay. The assembly of the end effector, lift and cab is what defines the crane (or crane assembly). The movements actually are controlled by the end effector The end effector references its associated lift, cab and bridge as illustrated in Figure 4.

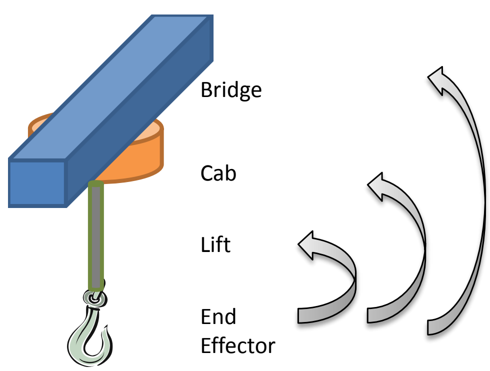
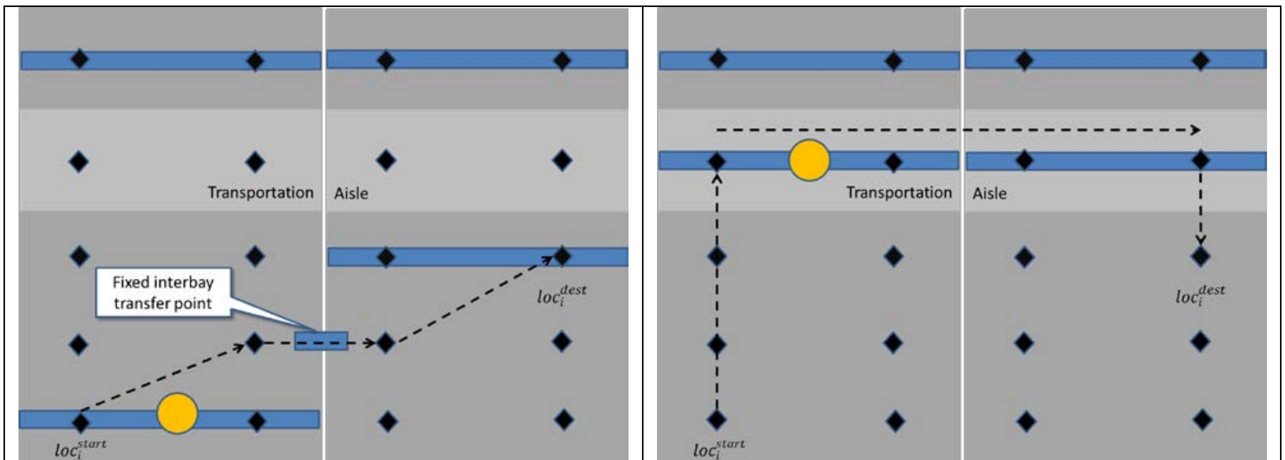


Figure 4: Object definitions and relationships in the crane library.

In addition to these 4 agent objects, there is bay. A bay is a fixed object that defines a rectangular region over which one or more bridges may move. Each bay has a fixed number of zones which are used to control bridge movements to prevent collisions. One bridge may occupy only one zone at a time and the zone can only be occupied by one bridge at a time. Therefore, a bay must have at least the number of zones as the number of bridges within the bay. Each bay has multiple drop-off and pickup locations defined as arbitrarily placed nodes. Multiple locations can exist within the same zone, and the locations do not need to be connected in a network. The examples below (Figure 5) show two bays with 3 zones each, 2 bridges and 1 crane. There are also multiple pickup and drop-off locations.

Bridges always stay within the same bay whereas a cabs (and associated lift and end effector) can move from one bridge to another bridge. This bridge movement happens only when moving from one bridge in one bay to another bridge in another bay. The transfers of cabs between bays are either done directly or within a transportation aisle. Direct transfers can done anywhere between the intersection of two bays or at predefined interbay transfer points while transportation aisle moves can only happen within a certain area (a zone) (Figure 5). There are properties on each bay that specify whether direct transfers can occur and which direction that they can occur (*RightBayOnly*, *LeftBayOnly* and *RightAndLeftBay*).



Direct Transfer	Transportation aisle transfer

Figure 5: Direct Transfer versus transportation aisle.

Objects in the crane library are defined as agents. They are autonomous, but do not have adaptive or learning features. In the Simio software architecture an "agent" is a superclass, and the crane class derives from the agent class. There is autonomous decision making at the object level. Objects requiring movement communicate their need for transportation, and cranes make decisions regarding what to transport based on their own internal logic, internal state, and model state.

4.4 Blocking, Deadlock Detection and Resolution

Deadlocks refer to conditions when two or more activities are waiting for each other to finish or more than two activities are waiting for resources in a circular chain. A system comprised of multiple bays and multiple cranes can easily deadlock when parts require a set of resources in a circular wait situation (Dotoli and Fanti, 2002; Dotoli et al. 2004). The bay object has a set of three properties that can help prevent deadlock from occurring. The first of these is a property named *Blocking Action* that controls the interaction between bridges. If specified as *Push Idle Bridge* then a busy bridge will automatically push an idle bridge out of the way to prevent a blocking situation. A second property named *Pre-check Zone Availability* can be used to force crane movements to wait until the necessary zones are available before starting a move. The third property named *Pre-check Cross Bay Availability* can be used to force crane movements to wait until all transportation aisle zones are free before starting a move. When used in conjunction these features prevent most deadlocks.

4.5 Verification and Validation

We worked with the customers throughout the process to verify that we were creating the right model vis-à-vis customer needs.

We verified that we were building the model correctly by employing a modular architecture and performing rigorous testing throughout the creation process to ensure that the model was behaving as we expected it to behave. A significant amount of effort was expended in the model creation and verification stages of the project. Developing model constructs to accurately capture the behavior of overhead cranes was a primary challenge, and robust testing was necessary to ensure that the model was built correctly. We tested both the behavior of the system and the times taken for that behavior.

We validated the model by testing that we build the right model, that is, that the model accurately represents the system of interest. Validating the behavior of the model requires us to run the model and compare the behavior of the simulated system with that of the actual system of interest. The goal is for the two systems to behave in a similar manner and rigorous testing demonstrated that the behavior of all the independent agents interacting with each other accurately represented the real system of interest. The input data consists exclusively of point estimates, so no statistical tests were performed.

To validate the model, we worked closely with the crane schedulers. Model fidelity was a key criteria for the project stakeholders. The cranes had to move at the same rates and adhere to the same practices that are followed in the facility. This requirement involved multiple rounds of development, testing, and demonstration to validate the model behavior. The primary means of validation were animation, face validity, and event validity (Sargent 2005). Figure 6 is a screen shot of the model during run time demonstrating the value of animation for model validation. Further validation focused on the moves made by each crane. We needed to make sure the model was picking the same set of bridges that would be used in practice. Various crane behaviors and logic were added to the model to increase the fidelity of the model and to help significantly increase stakeholder buy-in.

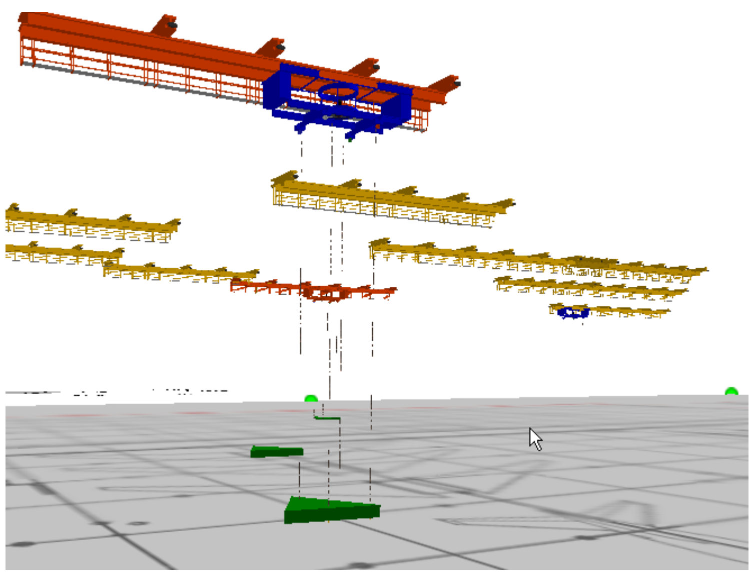


Figure 6: Screen shot of the model during run-time. Such views and animation were used for model validation.

Initially, not all move types were considered in an effort to streamline model development. Development, testing, and validation continued in an iterative fashion, including the addition of more complicated move types. For example, the facility includes several fixed interbay transfer points that are used when the transportation aisle is likely to be congested. This scenario is more likely to occur when investigating full schedules across multiple product lines, so this capability was added later in the development process after basic development and validation had occurred. Again, this addition increased the fidelity of the model and allowed for more detailed and accurate schedule evaluation.

5 SIMULATION FINDINGS AND RESULTS

5.1 System Metrics

Several metrics are measured to determine schedule performance. Based on conversations with the customer, the primary measures of schedule performance include total lateness, ratio of completed moves to scheduled moves and the ratio of cancelled moves to scheduled moves. Each scheduled move is defined by a start time t_i^{start} (see section 4.1 for details). At that clock time in the simulation, the object to be moved will request a crane to initiate the move. The time that the request is successful is recorded in the model as t_i^{actual} for the i^{th} move. The total lateness of an evaluated schedule is given by $\sum_{i=1}^{M}(t_i^{actual} - t_i^{start})$ for M moves. A move requires two capacity-constrained resources for execution: a cab and a crew. If capacity of these resources is unavailable at the time of move initiation, the model will attempt additional requests as capacity becomes available. The maximum number of resource request attempts is a model-level property that can be set at run time. If the move cannot seize all units of required resources within this number of requests, the move is cancelled and the cancellation is tallied in the variable *CancelledMoves*. The total number of move requests is stored in a model-level variable called *TotalMoveRequests*. Alternatively, if the move is successful the variable *CompletedMoves* is incremented. A move may result in a third state: uncompleted, which can be due to a deadlock or the end of the simulation run before the move can be initialized. The number of deadlocked or uncompleted moves is determined by *IncompleteMoves = TotalMoves-CancelledMoves-CompletedMoves*. Schedule feasibility metrics include *CompleteMoves/TotalMoves* and *CancelledMoves/TotalMoves*. The ratio *TotalMoveRequests/TotalMoves* is also a useful metric that indicates the overall congestion in the evaluated schedule.

5.2 Model Output and Decision Support

A method to highlight potential bottlenecks and highly utilized resources was need evaluate the schedule. A Gantt chart was chosen to display this data (Figure 7). The Gantt chart was able to show the seizing and releasing of resources over time. Bays, bridges, cranes and crews were all setup as resources and shown on the Gantt chart. The Gantt chart became a great way to monitor the allocation of resources over time.

The cranes on the Gantt only show the duration between moving a material from one location to another. The bays, bridges and crew pools show the seizing of the resources of the associated crane with material and without material. They capture the transfer time to move to the pickup point, pickup, delivery the material and return home after the material has been delivered.

Figure 7: Gantt chart showing resource usage during a model run, including cabs and bays.

5.3 Experimentation Results

The model was also used to experiment with the performance of a schedule under different scenarios. The two decision variables are the number of crews available and the maximum number of requests for a given move. Primary outputs are total lateness, ratio of completed moves to total moves, and ratio of number of move requests to total moves. Results for an example schedule are shown in Table 3.

Table 3. Experimentation results

Scenario	Total Moves	Max Requests	Number of Crews	Lateness	Moves Completed	Moves Cancelled	Move Requests	$CompleteMo$ $/TotalMoves$	$CancelledMo$ $/TotalMoves$	$TotalMoveRequ$ $/TotalMoves$
1	78	10	1	14.5628	12	0	182	15.38%	0.00%	2.333333
2	78	10	2	501.454	74	0	406	94.87%	0.00%	5.205128
3	78	10	3	58.2781	78	0	372	100.00%	0.00%	4.769231
4	78	10	4	33.5349	78	0	360	100.00%	0.00%	4.615385
5	78	10	5	31.3186	78	0	358	100.00%	0.00%	4.589744
6	78	5	1	4.88654	7	1	146	8.97%	1.28%	1.871795
7	78	5	2	5.0511	10	1	162	12.82%	1.28%	2.076923
8	78	5	3	55.1227	40	5	260	51.28%	6.41%	3.333333
9	78	5	4	41.0586	43	6	262	55.13%	7.69%	3.358974
10	78	5	5	25.0973	49	21	334	62.82%	26.92%	4.282051

5.1 Strengths and Limitations

The model was initially developed as a deterministic model due to customer needs – the initial need was for a means of evaluating potential schedules for both feasibility and performance. However, the model was developed to allow for stochastic behavior. Primary sources of randomness in the system include the times at which transportation resources are needed (which can vary due to randomness in production system), time needed for actual transportation (moving, connecting, and disconnecting), and low-probability events such as machine failures. The stochastic implementation can be used to evaluate not only schedule feasibility but schedule risk.

The model was developed with a flexible architecture that lends itself to future expansion. Cranes are modeled as independent agents in a larger discrete event framework. Future work may include optimization implemented in the model itself, or alternatively inserting the model into a more sophisticated optimization system. The scheduling system itself described in this paper is treated as a proprietary black-box scheduling methodology. There is potential to develop a more robust stochastic optimization approach. There is also potential to improve upon the agents in the model. For example, to allow for more sophisticated interaction and negotiation between agents, or to implemented adaptive learning behavior.

6 CONCLUSION

This paper described the evaluation of complex crane schedules in a large-scale manufacturing environment. A simulation-based approach was well suited due to the scale and complexity of the system under study. A 3D object-oriented simulation platform with both discrete event and agent-based paradigms was selected to enable modeling of detailed crane logic. A custom but flexible library of agent objects was developed that enabled translation of the conceptual model into an executable tool. Schedule evaluation consists of the crane schedulers inputting a formatted schedule via commercial off the shelf spreadsheet software and then running the model. Model results include measures of schedule feasibility and fitness. These metrics can be used to choose a preferred schedule, mitigate existing schedule risks, or provide decision support for production system improvements.

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