button of the Animate toolbar. A graphical Storage T-bar graphically depicts the entities in a storage facility.

- The Seize button allows the modeler to define a so-called seize area to animate entities seizing a resource.
- The Parking button allows the modeler to define a so-called parking area to animate parking areas for transporters.
- The Transporter button allows the modeler to design a visual representation (picture) for a transporter.
- The Station button allows the modeler to specify an icon for a particular Station module.
- The Intersection button allows the modeler to specify an intersection in a network of automated guided vehicles (AGVs). These are transporter-type objects that must keep track of their positions in the system to avoid collisions. AGVs are not covered in this book.
- The Route button is used to specify the animation path for moving entities in the system.
- The Segment button is used to specify the animation path of a conveyor.
- The Distance button is used to specify the animation path of a transporter.
- The Network button is used to specify the animation path of an AGV. Unlike ordinary transporters, Arena endows AGVs with the capability of sensing each other to avoid collisions.
- The Promote Path button is used to promote a visual line to an animation path of a desired object.

The use of the Animate Transfer toolbar and various transportation-related modules will be illustrated in three examples in the sequel.

### 13.3 EXAMPLE: A BULK-MATERIAL PORT

Bulk materials are an important component of international trade, and their transportation is mediated by numerous seaports worldwide. Important bulk materials include iron ore, cement, bauxite, grain, oil, and coal. For analysis of port facilities, see Altiok (1998), White (1984), and Crook (1980).

This example illustrates bulk port operations, using the notions of station, entity routing among stations, entity pick-up and drop-off by another entity, and the control of entity movements using logical gating. It concerns a bulk material port, called Port Tamsar, at which cargo ships arrive and wait to be loaded with coal for their return journey. Cargo ship movement in port is governed by tug boats, which need to be assigned as a requisite resource. The port has a single berth where the vessels dock, and a single ship loader that loads the ships. A schematic representation of the layout of Port Tamsar is depicted in Figure 13.2.

Port Tamsar operates continually 24 hours a day and 365 days a year. The annual coal production plan calls for nominal deterministic ship arrivals at the rate of one ship every 28 hours. However, ships usually do not arrive on time due to weather conditions, rough seas, or other reasons, and consequently, each ship is given a 5-day grace period commonly referred to as the lay period (see Jagerman and Altiok [1999]). We assume that ships arrive uniformly in their lay periods and queue up FIFO (if necessary) at
an offshore anchorage location, whence they are towed into port by a single tug boat as soon as the berth becomes available. The tug boat is stationed at a tug station located at a distance of 30 minutes away from the offshore anchorage. Travel between the offshore anchorage and the berth takes exactly 1 hour. We assume that there is an uninterrupted coal supply to the ship loader at the coal-loading berth, and that ship loading times are uniformly distributed between 14 and 18 hours. Once a ship is loaded at the berth, the tug boat tows it away to the offshore anchorage, whence the boat departs with its coal for its destination. Departing vessels are accorded higher priority in seizing the tug boat.

An important environmental factor in many port locations around the world is tidal dynamics. Cargo ships are usually quite large and need deep waters to get into and out of port. Obviously, water depth increases with high tide and decreases with low tide, where the time between two consecutive high tides is precisely 12 hours. We assume that ships can go in and come out of port only during the middle 4 hours of high tide. Thus, the tidal window at the port is closed for 8 hours and open for 4 hours every 12 hours.

We wish to simulate Port Tamsar for 1 year (8760 hours) to estimate berth and ship loader utilization, as well as the expected port time per ship. We mention parenthetically that although a number of operating details have been omitted to simplify the modeling problem, the foregoing description is quite realistic and applicable to many bulk material ports and container ports around the world.

An Arena model of Port Tamsar consists of four main segments: ship arrivals, tugboat operations, coal-loading operations at the berth, and tidal window modulation. These will be described next in some detail along with simulation results.

### 13.3.1 Ship Arrivals

Ship arrivals are implemented in the Arena model segment depicted in Figure 13.3. Ship arrivals are generated deterministically by the Create module, called Vessel Arrivals, at the rate of one ship every 28 hours. On creation, a ship entity immediately proceeds to the Delay module, called Lay Period, where it is delayed uniformly between
0 and 120 hours to model an actual arrival within its lay period. The dialog boxes of modules *Vessel Arrivals* and *Lay Period* are displayed in Figure 13.4.

In due time, the ship entity enters the *Assign* module, called *Mark Arrival Time*, where its (actual) arrival time is stored in its *ArrTime* attribute. The ship entity then enters the *Seize* module, called *Get Berth*, whose dialog box is displayed in Figure 13.5.
Here, the ship entity attempts to seize the berth, and waits in queue \textit{Get Berth.Queue} while resource \textit{Berth} is occupied.

Once a ship succeeds in seizing resource \textit{Berth}, it enters the \textit{Hold} module, called \textit{Inbound Wait for Tug Boat}, whose dialog box is displayed in Figure 13.6. More specifically, the ship entity waits in the queue \textit{Inbound Wait for Tug Boat.Queue} until the tugboat becomes available (note the \textit{Infinite Hold} option in the \textit{Type} field). The Tugboat segment will ensure that the tugboat constantly monitors that the queue \textit{Inbound Wait for Tug Boat.Queue} has ships waiting to be towed into port and that the high-tide condition is satisfied.
13.3.2 Tug Boat Operations

Tug boat operations are implemented in the Arena segment depicted in Figure 13.7. At time 0, a single entity representing the tug boat is created by the Create module, called Create Tug, whose dialog box is displayed in Figure 13.8. The newly created tug boat entity then proceeds to the Station module, called Tug Station, whose dialog box is displayed in Figure 13.9.

Station modules are used in this model as entry points to a geographic location or to a set of modules representing a logical segment of the model. As will be seen later,
Route modules (from the Advanced Transfer template panel) are used to shuttle entities among Station modules. The blank (unused) fields in Figure 13.9 are related to modeling automated guided vehicles (AGVs), which are outside the scope of this book.

Having entered module Tug Station, the tug boat entity proceeds to the Hold module, called Monitor Need for Tug Boat, whose dialog box is displayed in Figure 13.10. Here, the tugboat entity continually monitors the queues Inbound Wait for TugBoat.Queue.

Figure 13.8 Dialog box of the Create module Create Tug.

Figure 13.9 Dialog box of the Station module Tug Station.
and **Outbound Wait for TugBoat.Queue** for ships calling on its services (see the **Condition** field). It also ensures that there is enough high-tide time to get a ship out of the queues and tow it to its destination.

Note that it takes a total of 1.5 hours to tow a ship from queue **Inbound Wait for TugBoat.Queue** and 2 hours from queue **Outbound Wait for TugBoat.Queue**. The global variable **HTF** in the **Condition** field stores the end time of the next high tide assigned in the **Assign** module, called **Open** (this will be further discussed in Section 13.3.4). More formally, the **Hold** module monitors the condition

\[(NQ(\text{Inbound Wait for TugBoat.Queue}) > 0 \ \text{and} \ \text{HTF} - t\text{now} > 1.5) \ \text{or} \ \ (NQ(\text{Outbound Wait for TugBoat.Queue}) > 0 \ \text{and} \ \text{HTF} - t\text{now} > 2)\]

which monitors the residual high-tide period and scans for ship entities waiting for the tug boat in either of the **Hold** module queues housing inbound or outbound ships. While the scan condition is false (no ships are waiting to be towed), the tug boat entity resides in queue **Monitor Need for TugBoat.Queue**. However, once the scan condition becomes true, it will immediately proceed to the **Decide** module, called **Who Wants Tug Boat**, whose dialog box is displayed in Figure 13.11. In this **Decide** module the tug boat entity finds out whether it is needed by an inbound ship or by an outbound ship (which has a higher priority), and proceeds accordingly to the appropriate queue.

**Decide** modules are used in our model to dispatch entities to requisite destinations probabilistically or depending on prevailing conditions, as indicated by the option selected in the **Type** field. Having selected the option **2-way by Condition**, the **If** field can be used to enter a predicate (condition) involving variables, attributes, entity types or expressions, including random ones, whose specification is then entered in the **Value**
field. In our case, when the expression in the Value field is true, the tug boat entity will proceed to tow an outbound ship (by transferring to the Route module, called Go to Departing Vessel Station); otherwise, it will proceed to tow an inbound ship (by transferring to the Delay module, called Go to Inbound Vessel). Note carefully how higher towing priority is given to outbound ships, by checking for their presence first.

The dialog box for the former Route module, called Go to Departing Vessel Station, is displayed in Figure 13.12. The Destination Type and Station Name fields indicate that the tug boat will transfer to the Station module, called Departing Vessel Station, while the Route Time and Units fields specify a 1-hour transfer time.

In addition to the Station option in the Destination Type field, the modeler may select a transfer destination option of type Sequential (the destination is specified via a Sequence spreadsheet module from Advanced Transfer template panel), Attribute (the destination is the value of an entering entity's specified attribute), or Expression (the destination is evaluated in an expression). Note that the Route module does not have an exit connection. Arena makes sure that the routed entity arrives at its destination at the end of its transfer time.

Figure 13.11 Dialog box of the Decide module Who Wants Tag Boat.

Figure 13.12 Dialog box of the Route module Go to Departing Vessel Station.
Recall that when a tow request is made by an inbound ship, the tug boat enters the Delay module, called Go to Inbound Vessel. Here, the tug boat is delayed for 30 minutes, which represents travel time to the anchorage area where the requesting ship resides in the queue Inbound Wait for Tug Boat Queue.

The tug boat entity next enters the Pickup module (from the Advanced Process template panel), called Pickup Inbound Vessel, whose dialog box is displayed in Figure 13.13. A Pickup module is used by an incoming entity to pick up other entities residing in a queue. The number of entities to be picked up is specified in the Quantity field starting from the queue position specified in the Starting Rank field. The queue itself is specified in the Queue Name field.

The picking entity and the picked-up entities form a group entity, where the picked-up members form an internal queue and are identified by their rank (position) in it. Since the picking entity may make several pickups (at different times or places), picked-up members of the group maintain their ID via their rank. As will be seen later, rank information may be used in entity drop-off.

Next, the tug boat enters the Route module, called Go to Loading Station, to model the 1-hour towing operation of an incoming ship to the loading station on the berth. The corresponding self-explanatory dialog box is displayed in Figure 13.14.

The remainder of the Arena model segment of Figure 13.7 (starting with the module, called Port Exit Station), pertains to departing ships and will be explained in the next section when we discuss ship departures.

### 13.3.3 Coal-Loading Operations

Coal-loading operations are implemented in the Arena segment depicted in Figure 13.15. To commence a coal-loading operation, the tug boat towing an inbound cargo ship enters the Station module, called Coal Loading Station, whose relevant part of the dialog box is displayed in Figure 13.16.

The tug boat then proceeds immediately to the Dropoff module, called Dropoff Inbound Vessel, whose relevant part of the dialog box is displayed in Figure 13.17. Here, the towed ship is separated from the tugboat, or in other words, the tugboat drops off the vessel (hence the module’s name). The Dropoff module is selected from the Advanced Process template panel, and is used in conjunction with the Pickup module.
Figure 13.14  Dialog box of the Route module Go to Loading Station.

Figure 13.15  Arena model segment implementing coal loading operations at Port Tamsar.

Figure 13.16  Dialog box of the Station module Coal Loading Station.
Entities entering a Dropoff module must be grouped entities, including the entity that picks up all other ones. The Quantity field specifies the number of entities to drop off, while the Starting Rank field specifies the rank of the entity in the group from which to start the drop-off. The Member Attributes field controls the attributes of the grouped entities. In Figure 13.17, the dropped-off entities are instructed to maintain their original attributes. The modeler can also stipulate that all new values or some of them be assigned to entity attributes via the options Take All Representative Values and Take Specific Representative Values, respectively.

Next, the picking entity and the picked-up entities exit the Dropoff module Dropoff Inbound Vessel and are routed to their destinations according to their specified connections. Consequently, the tug boat enters next the Route module, called Go Back to Tug Station, which routes the tug boat entity (after a 1-hour delay) to the Station module, called Tug Station, located in the tug boat operations segment of Figure 13.7. Simultaneously, the towed-ship entity proceeds to seize the loader by entering the Seize module, called Seize Loader, whose dialog box is displayed in Figure 13.18. Note that at this
time the loader is always available, since the previous departing ship (if any) must have already released it. Once the loader is seized, the ship entity proceeds to the Delay module, called Loading Time, to model a uniform loading time between 14 and 18 hours.

Following the loading delay, the ship entity releases the loader and berth resources simultaneously by entering the Release module, called Release Loader and Berth, whose self-explanatory dialog box is displayed in Figure 13.19.

Finally, the ship entity proceeds to the Hold module, called Outbound Wait for Tug Boat, to await its turn to be towed to the anchorage by the tugboat. The dialog box of this module is analogous to that of the Hold module, called Inbound Wait for Tug Boat, in the ship arrivals segment shown in Figure 13.3. As soon as the ship entity is placed in the queue Outbound Wait for Tug Boat.Queue, the tugboat entity will be dispatched in due time from module Tug Station in the tugboat operations segment of Figure 13.7 to module Departing Vessel Station in the coal-loading segment of Figure 13.15. It then enters the Pickup module, called Pickup Vessel, whose dialog box is displayed in Figure 13.20. The tugboat entity picks up the waiting ship entity.

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**Figure 13.19** Dialog box of the Release module Release Loader and Berth.

**Figure 13.20** Dialog box of the Pickup module Pickup Vessel.
and proceeds to the port exit by entering the Route module, called Go to Port Exit Station, which routes it 1 hour later to module Port Exit Station in the tug boat operations segment of Figure 13.7. Note that at this point the tug boat and ship entities left the coal-loading operations segment of Figure 13.15, and entered the tug boat operations segment of Figure 13.7. The tug boat entity then drops off the ship entity with its original attributes in the Dropoff module, called Dropoff Departing Vessel, and proceeds immediately to module Tug Station (both in the tug boat operations segment of Figure 13.7). The trip distance is assumed negligible, and therefore the trip is instantaneous.

The ship entity itself proceeds to the Record module, called Tally Port Time, whose dialog box is displayed in Figure 13.21, to record its sojourn time in the port (port time). To this end, the ship entity makes use of its ArrTime attribute that previously recorded its arrival time at the port, taking advantage of the fact that the drop-off retained its original attributes. Finally, the coal-loaded ship entity departs the port via a Dispose module.

13.3.4 **TIDAL WINDOW MODULATION**

Tidal window modulation is implemented in the Arena segment depicted in Figure 13.22. This segment creates the tidal window and modulates its opening and closing, using the variable Tidal Window to represent the tidal state. A value of 0 codes for unfavorable tidal conditions (closed tidal window), while a value of 1 codes for favorable tidal conditions (open tidal window). Thus, all vessels can determine from the value of the variable Tidal Window whether they may move into or out of port.

A tidal window entity is created at time 0 in the Create module, called Create Tidal Window, whose dialog box is displayed in Figure 13.23. Note that since the First Creation field is 0.0 and the Max Arrivals field specifies precisely one arrival, the values of fields in section Time Between Arrivals are irrelevant.

The created tidal window entity first enters the Assign module, called Close, whose dialog box is displayed in Figure 13.24. Here, the variable Tidal Window is set to 0.
Figure 13.22  Arena model segment implementing tidal window modulation at Port Tamsar.

Figure 13.23  Dialog box of the Create module Create Tidal Window.

Figure 13.24  Dialog box of the Assign module Close.
(closed tidal window), after which the tidal window entity proceeds to the Delay module, called Window Closed, to maintain this tidal state for a duration of precisely 8 hours.

In a similar vein, the tidal window entity then enters the Assign module, called Open, whose dialog box is displayed in Figure 13.25. Here, the variable Tidal Window is set to 1 (open tidal window), and the end time of the high tide (i.e., \( T_{\text{now}+4} \)) is stored in variable HTF. The variable HTF is checked by the tug boat before attempting any ship towing.

Next, the tidal window entity proceeds to the Delay module, called Window Open, to enable maritime traffic for 4 hours. The tidal window entity is then routed back to module Close to repeat the 12-hour tidal cycle.

### 13.3.5 Simulation Results for the Bulk Port Model

Port Tamsar was simulated for 1 year (8760 hours of continual operation), and the simulation results from one replication (obtained from the Queue option of the Category Overview section, the Resource option of the Category by Replication section, and the User Specified section) are displayed in Figure 13.26.

The waiting time of coal ships in queue Get Berth.Queue for the loading berth averaged about 16.19 hours. For outbound ships, the waiting time for the tug boat was about 5.91 hours. However, the corresponding waiting times for inbound coal ships averaged about 6.66 hours, due to their lower priority. The tug boat’s average waiting time between towing assignments averaged some 19.99 hours.

The Resource section reveals that berth utilization was 83.38% and loader utilization was 56.29%. The discrepancy is due to the fact that a ship seizes the berth first from
the anchorage location, and consequently, berth utilization is inflated by inbound waiting times for the tug boat as well as travel times to the berth. In contrast, loader times consist solely of loading times. Finally, the sojourn times of cargo ships in the port averaged 46.57 hours. Note that estimating tug boat utilization would require keeping track of all tug boat busy periods in order to calculate the requisite time average using Time-Persistent statistics.

The simulation results of Figure 13.26 suggest that the berth constitutes a bottleneck at Port Tamsar, which slows the system down, giving rise to over 16 hours of waiting at the anchorage (partially due to waiting for an open tidal window). From the port authority’s point of view, long waiting times are financially deleterious, since ship owners may charge the port authority for excessive delays at the port (the so-called demurrage cost). To reduce the wait, ports may employ, in practice, multiple tug boats and loading berths to allow more ships to enter the port when the tidal window is open.

One way to attain this goal is to reduce the lay period, as this would reduce the variability of actual arrival times, and subsequently would also reduce mean waiting times at the anchorage. For example, Figure 13.27 displays simulation results for a lay period of 2 days (down from 5 days in Figure 13.26). Indeed, the average ship waiting time at the anchorage for berth availability (in queue Get Berth.Queue) consequently dropped to about 7.46 hours (down from about 16.19 hours in Figure 13.26). The results verify the well-known queueing principle that more regular arrivals give rise to shorter waiting times.
13.4 EXAMPLE: A TOLL PLAZA

This example concerns a transportation system consisting of a toll plaza on the New Jersey Turnpike, and aims to study the queueing delays resulting from toll collection. The system under study is depicted in Figure 13.28.

The toll plaza consists of two exact change (EC) lanes, two cash receipt (CR) lanes, and one easy pass (EZP) lane. Arriving vehicles are classified into three groups as follows:

1. Fifty percent of all arriving cars go to EC lanes, and their normal service time distribution is Norm(4.81, 1.01). Recall that only the non-negative values sampled from this distribution are used by Arena (see Section 4.2).
2. Thirty percent of all arriving cars go to CR lanes, and their service time distribution is 5 + Logn(4.67, 2.26).
3. Twenty percent of all arriving cars go to EZP lanes, and their service time distribution is 1.18 + 4.29 x Beta(2.27, 3.02).

Figure 13.27 Simulation results for the Port Tamsar model with shorter lay periods.