How to build agent based models. Field service example

Agent based modeling is the easiest modeling method. You identify which objects in the real system are important for solving the problem, and create those same objects in the model. You think of the behavior of those objects relevant to the problem, and program that same behavior in the model. You do not have to exercise your abstraction skills as much as in system dynamics or force yourself to "always think in terms of a process," as in discrete event modeling.

Described in one page, the process of building an agent based model includes answering the following questions:

1. Which objects in the real system are important? These will be the agents.
2. Are there any persistent (or partially persistent) relationships between the real objects? Establish the corresponding links between the agents.
3. Is space important? If yes, choose the space model (2D, 3D, discrete) and place the agents in the space. If the agents are mobile, set velocities, paths, etc.
4. Identify the important events in the agents' life. These events may be triggered from outside, or they may be internal events caused by the agent's own dynamics.
5. Define the agents' behavior:
   - 5.1. Does the agent just react to the external events? Use message handing and function calls.
   - 5.2. Does the agent have a notion of state? Use a statechart.
   - 5.3. Does the agent have internal timing? Use events or timeout transitions.
   - 5.4. Is there any process inside the agent? Draw a process flowchart.
   - 5.5. Are there any continuous-time dynamics? Create a stock and flow diagram inside the agent.
6. Do agents communicate? Use message sequence diagrams to design communication/timing patterns.
7. What information does the agent keep? This will be the memory, or state information, of the agent. Use variables and statechart states.
8. Is there any information, and/or dynamics, external to all agents and shared by all agents? If yes, there will be a global part of the model (the term "environment" is sometimes used instead).
9. What output are you looking for? Define the statistics collection at both the individual and aggregate levels.

In this chapter, we give a very detailed description of a model design process, from the very beginning to the optimization results and assumptions discussion.

The problem statement

A fleet of equipment units (for example, wind turbines or vending machines) are distributed geographically within a certain area. Each equipment unit generates revenue while it is working. However, it sometimes breaks down and needs to be repaired or replaced. Maintenance is due every maintenance period. Late maintenance, as well as advanced age, increase the probability of failure.

Wind turbines

The service system consists of a number or service crews that are based in a single central, or "home," location. When a service or maintenance request is received by the service system, one of the crews takes it, drives to the equipment in question, and performs the required work. During the failure examination, it may turn out that the equipment cannot be repaired, in which case it is replaced. If already due, any currently scheduled maintenance is done after the repair, within the same visit. (The service crew can also replace aged equipment even if it is still working, subject to the replacement policy.) Having finished the work, the service crew may take another request and drive to the next unit location, or, if there are no requests, return home.

A service crew has constant daily costs associated with it. Each operation (maintenance, repair, or replacement) has an additional one-time cost. All parameters of the system are listed in the Table.

Parameter	Value
Daily revenue per working equipment unit	$400
Daily cost of a service crew, including driving costs	$1,500
Average repair cost	$1,000
Maintenance cost	$600
Replacement cost	$10,000
Typical repair time	5 hours
Typical maintenance time	3 hours
Typical replacement time	12 hours
Probability replacement needed after failure	10%
Maintenance period	90 days
Base failure rate (maintenance done, equipment not aged)	3 / 100 days
Service crew mobility	500 miles / day
Equipment units in the fleet	100
Area serviced	600 x 500 miles

The goal of this model is to find the number of service crews, and the replacement policy, that result in maximum profit for the equipment fleet.

Phase 1. Can be done on paper

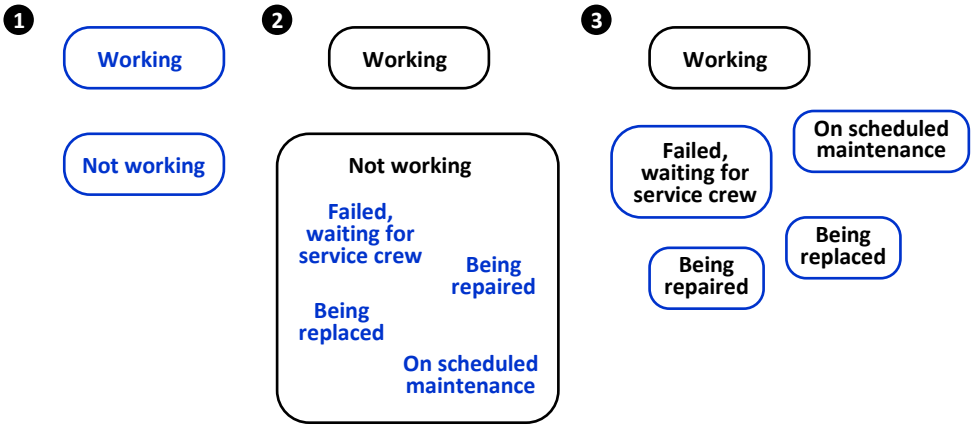
Who are the agents?

As we said earlier, mapping the problem to the modeling language is easy in the agent based modeling paradigm. What objects in the real system do we observe and are interested in? Equipment and service crews. So, these will be the agents in our model. Do we need a central service dispatcher of any kind, or any environment objects? We will find out later during the model building process.

Agents in the field service model

Equipment unit agent

We definitely do want to know if the equipment is working or not. So we will distinguish between at least two *states* of the equipment unit – **Working** and **Not working**, – and will try to use the *state transition diagram* to model the equipment behavior, see the Figure version 1.

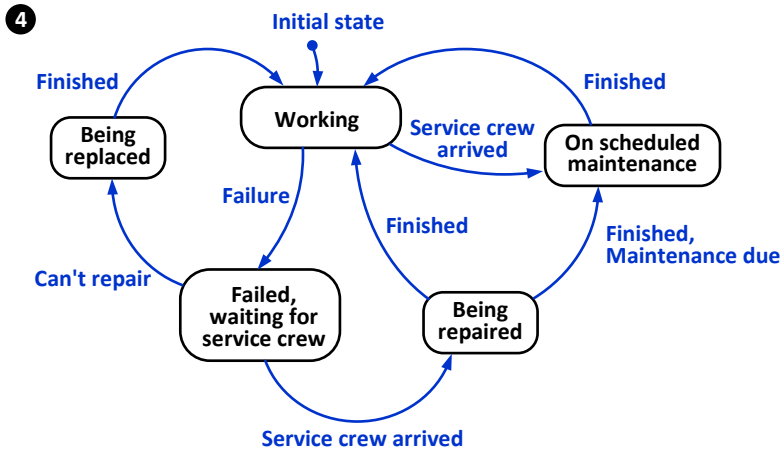


State transition model of the equipment unit, versions 1, 2, and 3

While the equipment is not working, it can be in failure (and be waiting for the service crew to arrive and fix it), be repaired or replaced, or be on scheduled maintenance, Figure version 2. Are these separate states or one state? Making these three separate states makes sense if:

- The behavior of the equipment unit is essentially different in different states – say, different time spent in the state, different reactions to the external events, or different actions taken upon exiting the state; or
- We want to have separate statistics for the states.

In our case, all arguments are for separate states. We do want to collect state-based statistics (for example, find out the average waiting time for the service crew); time of operations is different; and behavior is different (for example, maintenance can be done directly after repair, but not after replacement). So, we end up with five states, see the Figure version 3.



State transition model of the equipment unit, version 4

Next, let us think of how the equipment *changes* its state. Initially, we will assume the equipment is **Working**. In the event of failure, the equipment transitions from the **Working** state to the **Failed** state. Then, after the service crew has arrived and examined the equipment, the state changes either to **Being replaced** or **Being repaired**. When this is complete, the equipment returns to the **Working** state. However, there is one exception: after repair, it may so happen that maintenance is due; in that case, maintenance is done immediately. Also, the service crew can go to the working equipment for scheduled maintenance. Now we have a tentative *state transition diagram*, see the Figure.

To complete the diagram, we need to determine *how the transitions are triggered*. **Failure** is clearly a stochastic event internal to the equipment. Both replacement and repair start upon the arrival of a service crew, so in fact, there is *only one* transition from the **Failed** state triggered by the crew arrival. This transition has two branches. One leads to **Being repaired**, and another to **Being replaced**. The decision is made internally, and is probabilistic according to the problem statement. Similarly, the transition from the **Being repaired** state taken upon repair completion has two branches as well. This time, the decision is deterministic: if maintenance is due, the next state is **On scheduled maintenance**; otherwise, the next state is **Working**. The transitions labeled

Finished are all time-driven, the time spent in a state corresponding to work being done can be obtained from the input data.

Notice that, depending on the state, the equipment unit reacts differently to the arrival of the service crew. If the crew comes to the working equipment, it can only mean it will do the scheduled maintenance, whereas, in the **Failed** state, it will examine the situation and repair or replace the equipment. It is also worth mentioning that, according to the semantics of statecharts, the transitions are *instantaneous* (take zero time), so in our statechart we assume the examination of failure takes zero time. This is a fair assumption: if we want, we can simply add this time to the duration of both replacement and repair.

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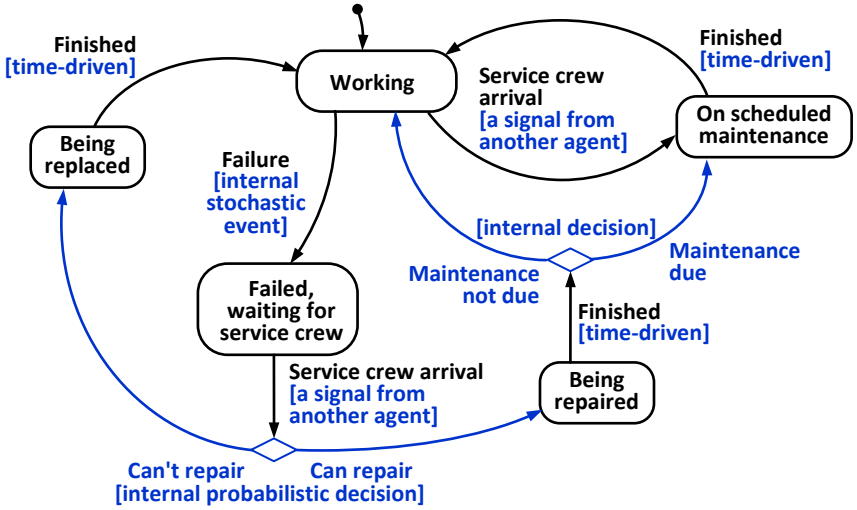


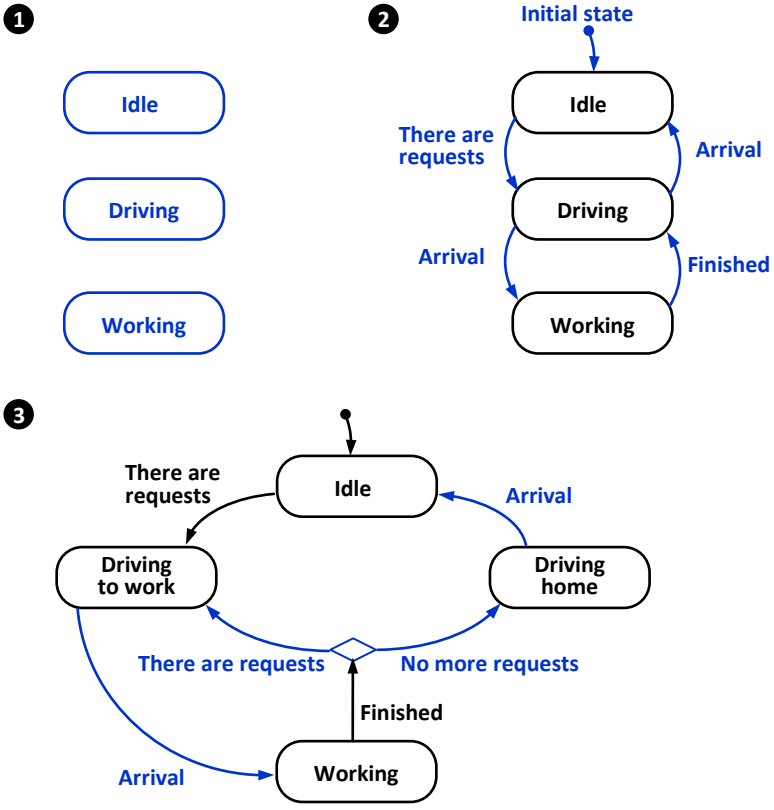
State transition model of the equipment unit, version 5

That's it for the equipment unit so far. We will add more details after we make some progress with the other parts of the model's design.

Service crew agent

The service crew behavior is simple: it takes a request, drives to the equipment unit, does the work, and either continues with the next request or returns to its home location. Unlike the equipment unit, the service crew is a mobile agent, so moving in space will be the essential part of its behavior. The notion of state, however, (**Idle**, **Driving**, **Working**) seems to be present here as well, so we will follow the same design pattern we used for the equipment unit, see the Figure version 1.

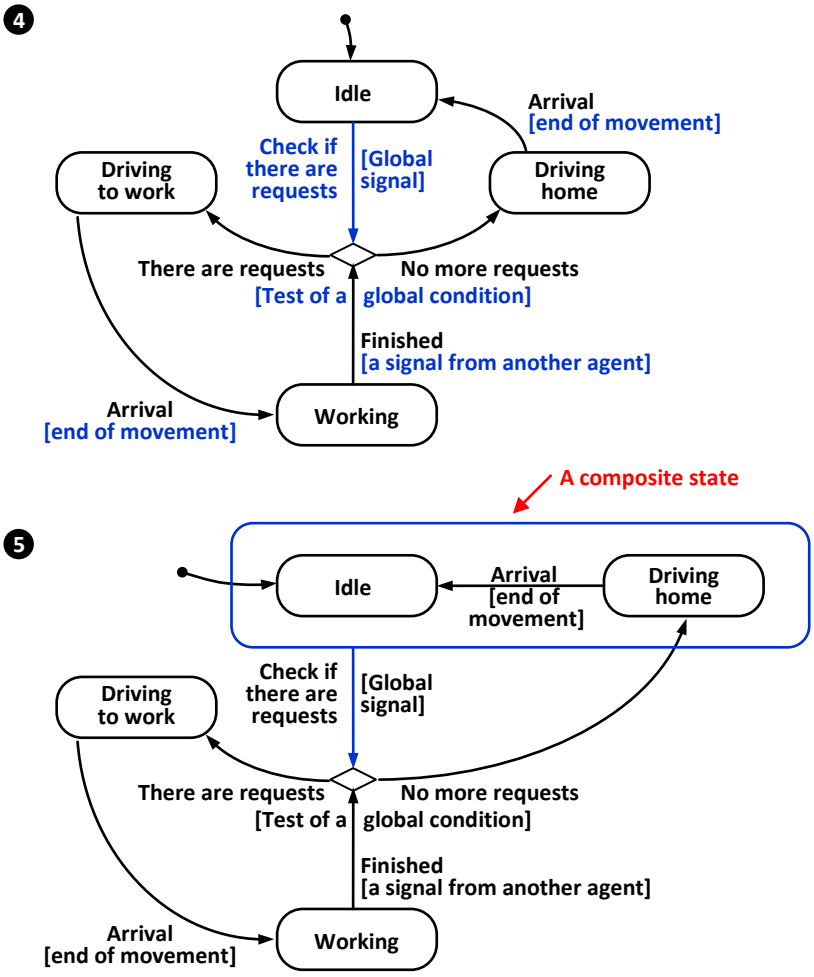
If we draw all possible states transitions, we will get what is shown in Figure version 2. There are two transitions from the **Driving** state, both triggered by **Arrival**. One leads to **Idle**, and the other to **Working**. The destination state depends on where the crew was driving. How do we capture this in the statechart? One way is to check the location upon arrival. Another, more elegant method is to have two different states for driving: **Driving to work** and **Driving home**. The decision of where to drive is made when the current task is completed (transition **Finished** triggered by the equipment's timing) and depends on whether or not there are more requests waiting to be serviced. This can be modeled by a construct we are already familiar with: a transition with two branches, see the Figure version 3.



State transition model of the service crew, versions 1, 2, and 3

In the resulting statechart there are two arcs labeled **There are requests**: one is from **Idle** state, and the other is a branch of the **Finished** transition. While in the latter case the condition is *tested once* upon completion of the current work assignment, in the former case the condition should be *constantly monitored* while the service crew is

idle. We will combine them into one: in **Idle** the service crew will be *explicitly told* to check if there are requests, see the Figure version 4. The reason for making this change in this case technical, based on the knowledge of agent based modeling. Multiple service crew agents may check the request queue at the same time, but there may be fewer requests than agents, so some will return to the **Idle** state (in our statechart: through the **Driving home** state, which will be passed through immediately in case the agent is already home).



State transition model of the service crew, versions 4 and 5

However, it may so happen that the notification about new requests comes while the service crew is driving home. In that case the crew will ignore it and, having arrived at the home location, will stay there, idle (until, most likely, another piece of equipment

breaks down). This is no good. We can assume the service crew is equipped with a radio and can take requests while driving. So, if the "check request" signal comes in the **Driving home** state, the crew will accept it, change the route, and drive to the equipment unit. In the statechart we could draw another transition triggered by the signal from the **Driving home** state to the decision diamond, but we will use a great statechart feature – a composite state.

A composite state is a group of states that have some common behavior – for example, the same reactions to events, or common timeouts.

The updated statechart of the service crew agent is shown in the Figure version 5. The transition **Check if there are requests** exits the composite state, and therefore applies *both* to the **Idle** and **Driving home** states. Note that transitions may freely cross the composite state borders; for example, the branch **No more requests** directly enters the **Driving home** state, and the initial state pointer points to the **Idle** state.

While designing the service crew behavior, we were constantly referencing the "request queue" and assuming somebody can "tell all agents" to check it out. The request queue is clearly global for all agents, as well as the central "dispatcher" that takes care of it. We will return to those items later on.

Agent communication. Message sequence diagrams

During the design of the service crew behavior, we used reasoning that goes like, "What will happen if a notification about the new requests comes while the service crew is driving home?" We have already started thinking about the agent communication and event ordering. In this section, we will introduce a graphical notation that greatly helps in communication design. This notation comes from the computer science world; namely, from the distributed systems area.

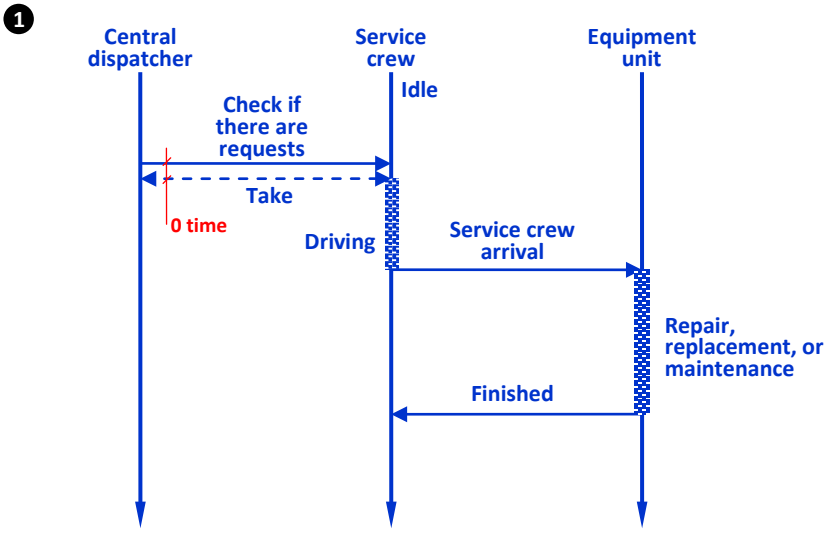
A good agent based modeler should know a little bit about the *design of distributed and parallel systems*. An agent based model is, in fact, a pseudo-distributed system: it is a collection of objects that are concurrently active and communicate with each other (despite the concurrency is simulated by the engine). Deadlocks, livelocks, unexpected simultaneous event ordering, and other problems specific to distributed systems are possible in agent based models.

Let's list all communication instances that we have used in our models of the equipment units and the service crews. They are:

- **Service crew arrival**: a message from a service crew to an equipment unit.
- **Finished**: a message from an equipment unit to the service crew.

- **Check if there are requests**: a message from a "central dispatcher" to all service crews.

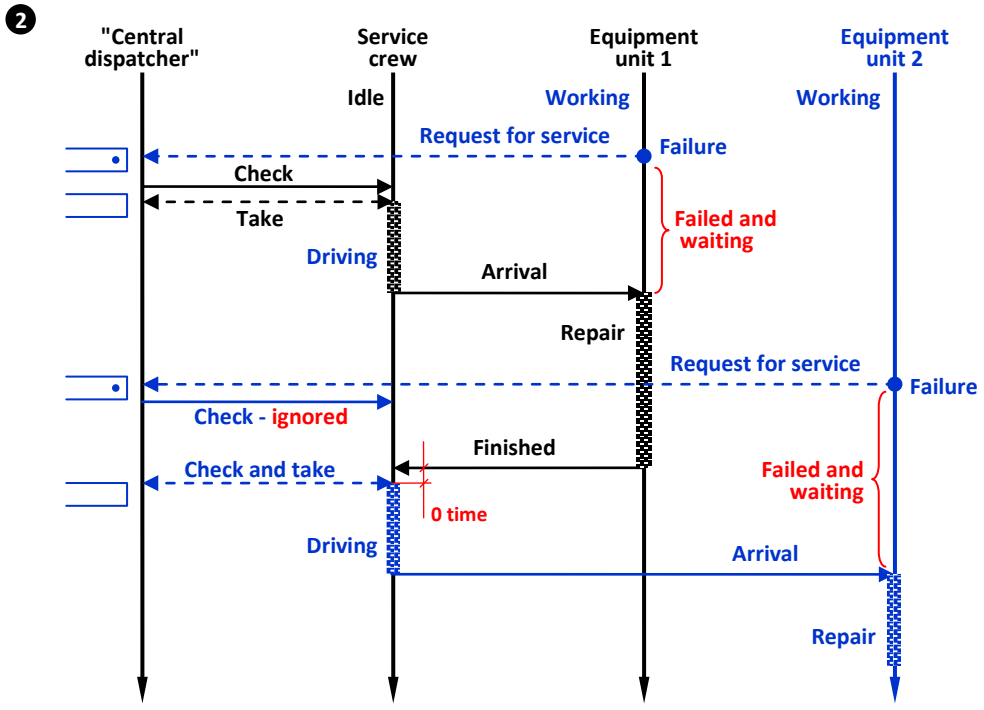
The best design notation for communication in concurrent systems is a *message sequence diagram*. In such a diagram, each object is represented by a vertical line, and messages (signals, function calls) from one object to another as horizontal arrows. Time flows downward. Time can be both physical (continuous) and logical (representing just event ordering with possibly zero intervals between events). Individual events local to an object can also be placed on a message sequence diagram.



Message sequence diagram of the field service model, version 1

The first version of a message sequence diagram for our model is shown in the Figure. There is just one equipment unit and one service crew. The shaded bars represent processes that take place inside the agents, and may end up with a message sent to another agent. Of course, both the service crew and the equipment unit are involved in the repair process; however, according to our model, it is the equipment unit that defines the duration or repair, and then notifies the service crew of completion.

However, in the Figure it is not clear who initiates the whole thing. We will now extend the diagram to include the equipment failure event. We will also add another equipment unit.



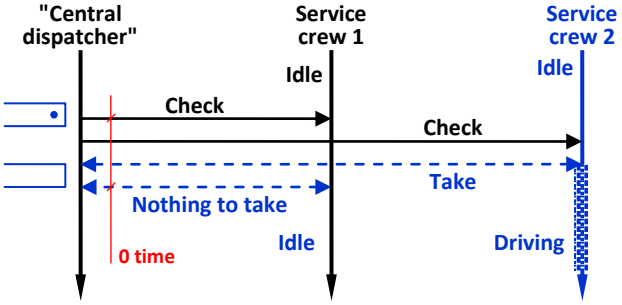
Message sequence diagram of the field service model, version 2

In version 2 of the message sequence diagram, we see the initial states of the agents: both equipment units are working, and the service crew is idle. Then, equipment 1 fails and posts a request to the "dispatcher." The "dispatcher" notifies the service crew, which immediately takes the assignment and starts driving to the failed equipment unit. While the first equipment unit is being repaired, failure occurs at the second unit. The request is posted and the "dispatcher" notifies the service crew, but this notification is ignored; the service crew is in the Working state and will not react to **Check request queue** messages, see the Figure. The service crew will not test the request queue and take another assignment until the first repair is completed.

Message sequence diagrams, in our case, are an auxiliary design document intended to help the modeler with understanding agent communication. They are not formal or executable, and they are not a part of the AnyLogic modeling language.

The last communication scenario we will draw is one with one service request and two crews, see the Figure. The "dispatcher" broadcasts the notification to all service crews. Both are idle, so both will check the queue. The events of checking the request

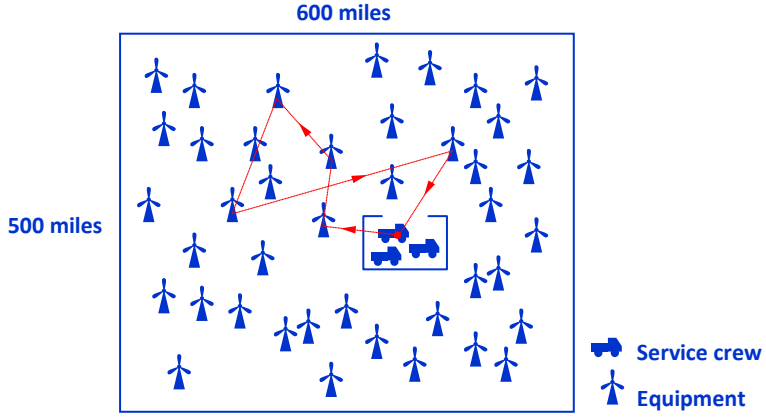
queue by the two agents are *simultaneous, but ordered*. Only one will take the assignment and start driving, while another will return to the **Idle** state.



Message sequence diagram of the field service model. Two service crews

Space and other things shared by all agents

Among the things shared by all agents is the space where equipment is located and service crews drive. With that in mind, we will define a 2D space of 600 by 500 model miles, distribute the equipment evenly across that space, and place the service crews initially into a home location also within that area, see the Figure. According to our simplified problem statement, we do not model roads; we just assume that, on average, a service crew can cover 500 miles in any direction if it drives for 24 hours. Thus, we will set up the speed for the service crew agents to 500 miles per day, and let them drive along straight lines directly from origin to destination.

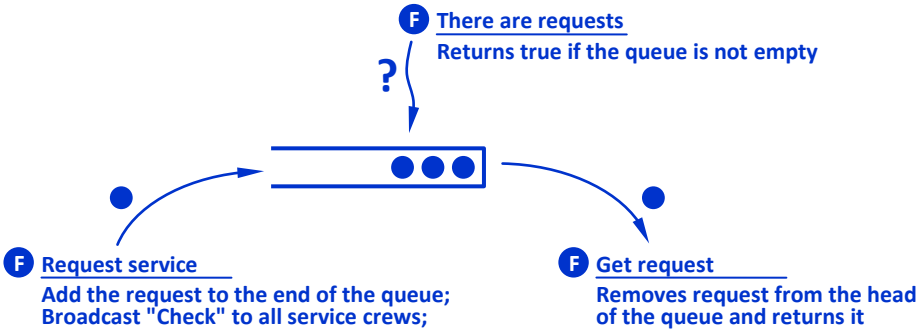


Space in the field service model

Apart from space at the global level, there are:

- The queue of service requests
- The "dispatcher" that manages the queue

How do we model this? Is the dispatcher active or passive? Does it have state or timing? The quick analysis of all we have said about it shows that the dispatcher does just one thing: it inserts a message in the queue and immediately broadcasts the notification to all service crews. *No state or timing*. Just stimulus and immediate response. This is best modeled as a *function call*. In addition, we can write functions that check the queue and remove the first request in the queue. See the Figure for this part of the model.



The queue of service requests and the "service dispatcher"

That's it for the first design phase. We have a sufficient level of detail to move the design to AnyLogic and run the model.

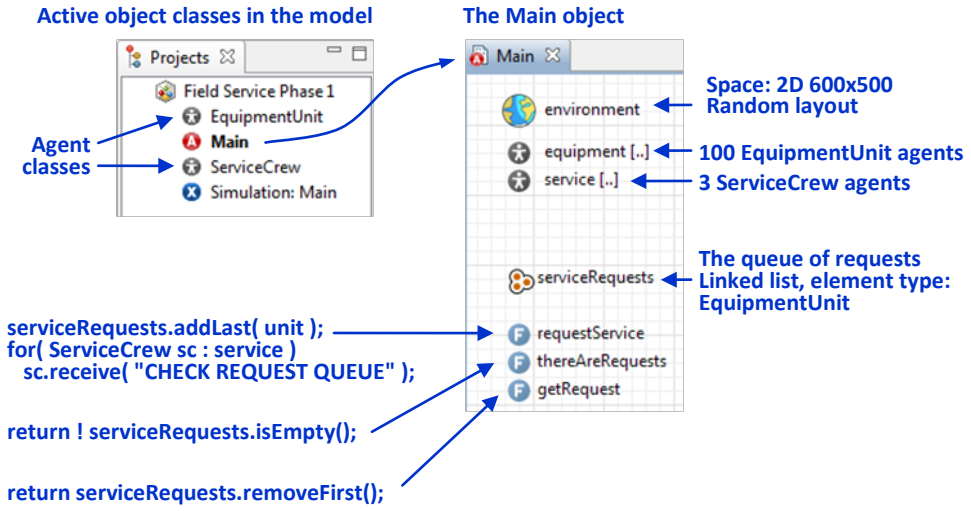
Phase 2. The model in AnyLogic. The first run

The model structure and the top level object Main

Mapping our design to the AnyLogic modeling language is straightforward. Equipment unit and service crew become agent classes **EquipmentUnit** and **ServiceCrew**, and all global things (space and request queue management) will be defined within **Main** – the top level object of the model. 100 equipment units (100 instances of **EquipmentUnit** class) and 3 service crews (just for example's sake) will be embedded into **Main**. Space and layout settings are defined in the **Environment** object, also in **Main**. Main will look like the Figure.

The queue of requests is modeled by AnyLogic collection of type linked list with elements of class **EquipmentUnit**.

Notice that we do not use a special data type for a service request – we just use the reference to the equipment unit that originates the request. This is good (because we follow the principle of minimalism), but it is only possible until we need to add more attributes to the request, such as timestamp, priority, or severity of problem.



The structure and the top level of AnyLogic Field service model

The function **requestService(EquipmentUnit unit)** adds the equipment unit provided as the argument to the end of the queue and iterates through all the agents in the **service** to deliver to them the message **"CHECK REQUEST QUEUE"** (the agent's function **receive()** immediately delivers the message to the agent). The **boolean** function **thereAreRequests()** calls the collection's method **isEmpty()** and returns its negation. The function **getRequest()** removes the last element of the queue and returns it.

The EquipmentUnit agent

The **EquipmentUnit** active object class is declared as agent. On the **Agent** page of its properties, the space type is set to **Continuous 2D** and the checkbox **Environment defines initial location** is selected.

The AnyLogic statechart of the equipment unit agent is shown in the Figure.

We encourage modelers to use colors to visually emphasize the meaning of states; for example, red for failure, green for up and running, etc. The same color scheme can then be used for statistics visualization.

Having drawn the statechart, we can specify the transition triggers. We have four transitions in this statechart that are time-driven (taken after the equipment unit has spent a certain time in a state):

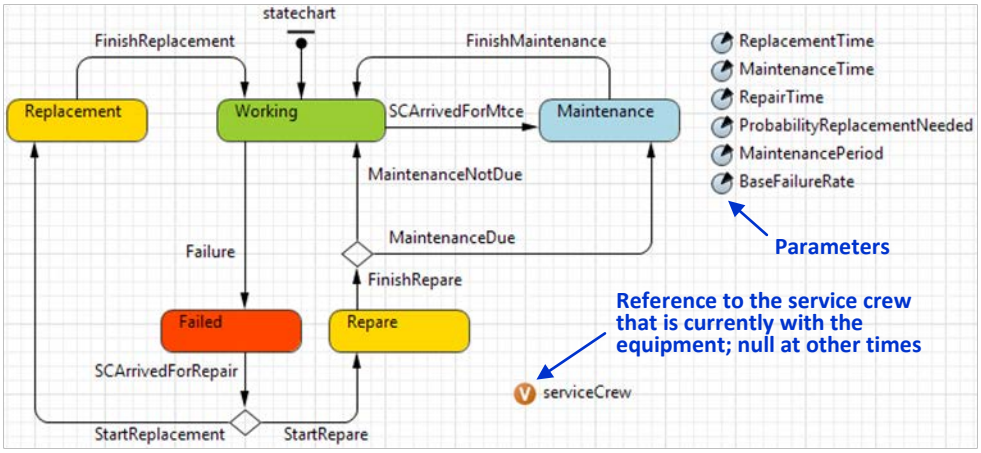
- **Failure** – time to failure depends, according to our problem definition, on many factors. For now, we will just set the trigger type to **Rate**, and rate to the

BaseFailureRate, which we will make a parameter. The transition of rate type works in the same way as the transition with exponentially distributed timeout.

- **FinishRepair** – we know the typical repair time and will assume a triangular distribution. The timeout for this transition will be
  triangular(RepairTime * 0.5, RepairTime, RepairTime * 2.5)
- **FinishReplacement** – similarly, stochastic timeout:
  triangular(ReplacementTime * 0.5, ReplacementTime, ReplacementTime * 1.5)
- **FinishMaintenance** – same as above:
  triangular(MaintenanceTime * 0.5, MaintenanceTime, MaintenanceTime * 1.5)

There are two remaining transitions that are triggered by a message received by the agent from another agent: **SCArrivedForRepair** and **SCArrivedForMtce**. We could use a text message like "SERVICE CREW ARRIVED", but we need to *remember the service crew in the equipment unit* because, at the end of work, it will be the equipment unit who notifies the service crew that it can leave. Therefore, we will use the reference to the service crew as the message type and save it in a local variable **serviceCrew**.

To establish a temporary link between agents, you can either call the agent's function **connectTo()** or simply remember a reference to another agent in a variable. The advantage of a variable is that we can explicitly specify the type of another agent and can identify the kind of relation in case there are many (like best friend, parent, colleagues). Don't forget to delete the reference (set the variable to **null**) when the relationship ceases to exist.



AnyLogic statechart of the EquipmentUnit agent

Two transitions in our model have branches; namely, **SCArrivedForRepair** and **FinishRepair**. Branch can be considered as an "if" statement executed when the

transition is taken. The condition of the branch **StartReplacement** is probabilistic: we know that, with a certain probability, the failed equipment cannot be repaired and needs to be replaced. In the AnyLogic language, this can be written as **randomTrue(ProbabilityReplacementNeeded)**. The alternative branch **StartRepair** will be set as the *default* and will be taken if the condition of **StartReplacement** evaluates to **false**. At the moment, we cannot write the condition for the **MaintenanceDue** branch because we do not know the date of the last maintenance; moreover, we have not yet modeled the maintenance scheduling at all. We will write **false** on that branch, and in the first version of our model it will never be taken.

We will now consider the *actions* associated with transitions. They are:

- **Failure** – here we need to place a service request. This is done though the **Main** object by calling its function **requestService()**. The **Main** object is the direct container of the **EquipmentUnit** agent (see the Figure), and there is a function **get_Main()** in the equipment unit that returns the **Main** object. The action of the **Failure** transition, therefore, is **get_Main().requestService(this);**. "**this**" is a reference to "self": the equipment unit provides it as an argument in the function call to identify who requests the service. That reference will then be placed in the request queue in **Main**.
- **SCArrivedForRepair** and **SCArrivedForMtce** – we need to remember the service crew in a local variable, so the action is **serviceCrew = msg;**. Here, **msg** is the message that triggered the transition.
- **FinishReplacement**, **FinishMaintenance**, and **MaintenanceNotDue** – all these transitions should release the service crew, so they have identical actions:
  send("FINISHED", serviceCrew);
  serviceCrew = null;

If you are observant, you may have noticed that these three transitions are the only transitions entering the **Working** state. So, each time the equipment enters the **Working** state, the same action gets executed. It is tempting to write the code releasing the service crew *just once* in the entry action of the **Working** state instead of writing it three times. However, the entry action will also be executed upon the statechart initialization when there is no service crew to release. Of course, you can test if **serviceCrew** in not **null**, etc., but to keep the design clean we will leave the code in the transitions; who knows what other transitions we may add to the statechart later that are not necessarily associated with the service crew release.

The last thing we would like to discuss before we switch to the **ServiceCrew** agent is the parameters. The six parameters we created are defined in the editor of the

EquipmentUnit agent; therefore, each equipment unit will have *its own copy* of **RepairTime**, **BaseFailureRate**, etc. Do we really need that? According to our problem statement, we don't: the parameters are global and apply to all equipment units. Unless we want to have different values in different units, having a copy in each unit is redundant and consumes memory (not an issue in this model, however). We could define the parameters in **Main**, but then the access to them from **EquipmentUnit** would look a bit ugly: **get_Main().RepairTime**. For simpler code writing, we will leave the parameters where they are.

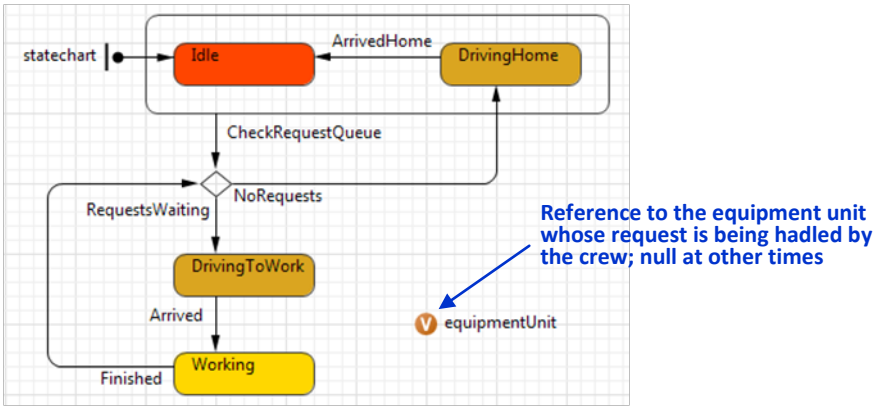
The ServiceCrew agent

This active object class is also declared as an agent. The initial location, however, is not defined by the environment, because we want the service crews to be initially "at home". So, we will explicitly place it there by writing the following **Startup code** of the agent:

```
Point pt = get_Main().home.randomPointInside();
setXY( pt.x, pt.y );
```

Here, **home** is a polyline drawn in the **Main** object. A random point inside that polyline is selected, and the agent is placed there by calling its function **setXY()**.

Another agent property we need to set up is speed. At the bottom of the **Agent** property, page we set **Velocity** to **500 / day()**. Here 500 model length units (one unit corresponds to one pixel in the editor) means 500 miles, which is consistent with the space settings of the environment object, see the Figure. **day()** is the duration of one day in model time units (if the model time unit is an hour, it returns 24; if it is day, it returns 1; and so on).



AnyLogic statechart of the ServiceCrew agent

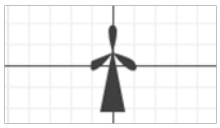
The AnyLogic statechart of the service crew is shown in the Figure. The transition triggers and actions are the following:

- **CheckRequestQueue** – triggered by the message **"CHECK REQUEST QUEUE"** sent by the function **requestService** of **Main**.
- **RequestsWaiting** – a branch ("ending" of the two transitions) taken if the condition **get_Main().thereAreRequests()** is true. Action of this branch is
  ```
  equipmentUnit = get_Main().getRequest();
  moveTo( equipmentUnit.getX(), equipmentUnit.getY() );
  ```
  Similarly to the **EquipmentUnit** class, the service crew temporarily remembers the equipment unit being serviced in the variable **equipmentUnit**. **moveTo()** is the built-in function of the agent that starts a straight movement to a given destination point.
- **NoRequests** – the default branch that is taken if the request queue is empty. The action of that branch is same as the Startup code of the agent:
  ```
  Point pt = get_Main().home.randomPointInside();
  moveTo( pt.x, pt.y );
  ```
  According to the statechart topology, this branch may follow both the transition **Finished** and the transition **CheckRequestQueue**. In the latter case, the service crew is already at home, but it still will make a small move to another location within the home polyline. This, of course, does not happen in reality, but it makes the statechart simpler by not bringing in any considerable error.
- **Arrived** – triggered by the agent's arrival. The action is:
  ```
  send( this, equipmentUnit );
  ```
  send() is the function of the agent that sends a message to another agent. (Compare this to the call of **receive()** function in **Main**, see the Figure. **Main** is not an agent, so for **Main** that was the only way of delivering a message.) The message is **this** – a reference to service crew itself.
- **ArrivedHome** – triggered by the agent arrival; no action.
- **Finished** – triggered by the message **"FINISHED"** set by the equipment unit, the action code erases the reference to the equipment: **equipmentUnit = null;**.

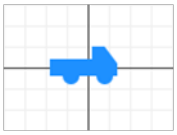
Animation

We will draw some schematic animation for equipment and service crew (see the Figure) so we see them on the "map" in **Main**. The animation of an agent should be drawn in the agent editor at the coordinate origin so that later on, in the global picture, it appears exactly where the agent is located.

If the animation of the active object was drawn after the object was embedded into a container, it will not appear on the container object diagram until you push the **Create presentation** button in the embedded object properties.



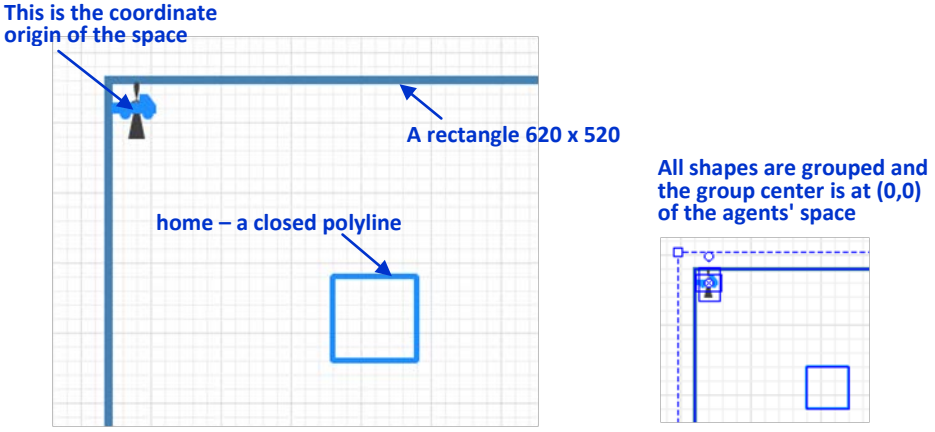
Equipment unit



Service crew

Animations of the agents at 300% zoom

In the **Main** object, we will set up the space where the whole thing will take place. According to the environment settings, the space is 500 x 600 pixels, and one pixel is one mile. The space coordinates are counted from the design-time position of the agent animation, so we will place both the equipment and service crew animations at the same place. We will also draw a rectangle around the space, slightly larger than it (say, 620 x 520 pixels), to visually show the space limits. Also, we will draw a **home** polyline in the middle of the space, see the Figure.

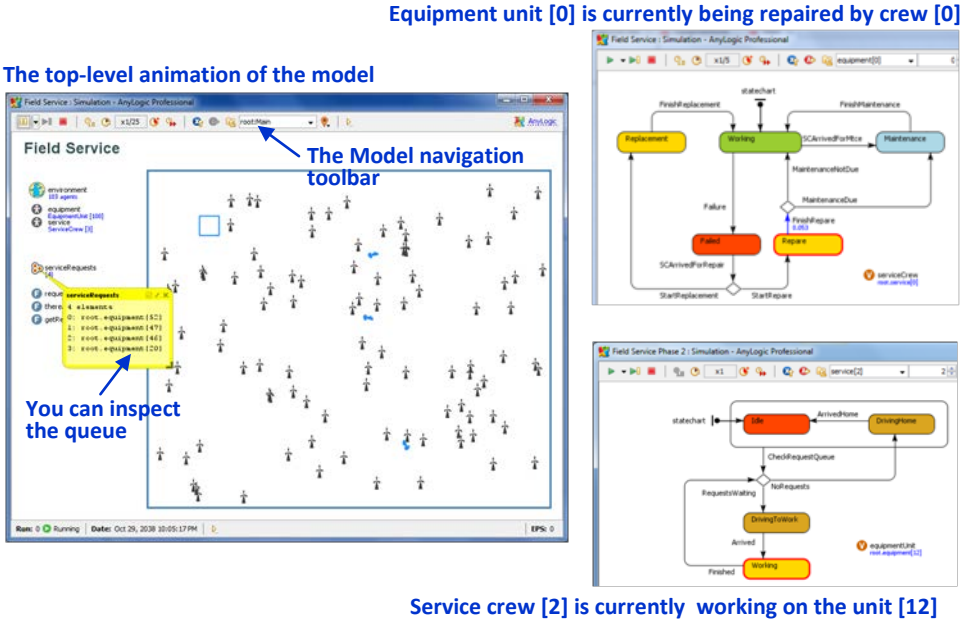


The animation of the model assembled in the Main object at 200% zoom

There is one thing we need to fix, however. While the agents' space (0,0) point is where the agents' animations are located, the home polyline's coordinates are counted from the coordinate origin of Main. So, calling **home.randomPointInside()** will return coordinates in a different system. To place the polyline in the same coordinate system as the agents, we should put it in a group with the center at the new coordinate origin. We recommend also adding the framing rectangle and the agent animations in that group, as well.

The first run

Now we can run the model. The top-level animation of the model is displayed in the Main (root) object – the first thing you see after you push the **Run the model** button. You can see how the service crews drive from one equipment unit to another – click the **serviceRequests** queue and inspect its contents.



The first run of the model. Top-level animation and internal view of agents

The great advantage of the object-centric agent-based modeling approach is that we can look inside any agent and see what it is doing, what is its state, variable values, connections, etc, see the Figure. The **Model navigation** section of the AnyLogic runtime toolbar can take you to any object in the model at any depth of the hierarchy.

Discussion and next steps

The main goal of the first runs of the model is to test it. The animation we created may not be needed by the end client, but it greatly helps to verify if the model is working as planned. All main parts of the model are in place now; however, the model at this stage is not yet able to answer our questions. Why not?

- We are not collecting any statistics in our model. We need to know the availability of equipment at any time, the utilization of the service, and many other things.

- Money still is to be added throughout the model. We need to calculate the revenue brought by the equipment and the cost associated with maintaining it.
- Some functionality is still missing (and some parts of the model have not yet been tested); we have not yet added the maintenance of the equipment and dependency of the failure rate on the equipment age and the timeliness of maintenance.
- We have not programmed the ability to experiment with either the number of service crews and the replacement policy.
- The visual impact of the model can be improved. For example, the color of the equipment unit animation can reflect its state; then, we can always visually assess the percent of working and failed equipment.

We will address these points in the next design phases.

Phase 3. The missing functionality

Maintenance, age, and failure rate

We will first focus on the missing functionality. According to our problem statement, maintenance is due every 90 days (the **MaintenancePeriod** parameter). When done on time, it decreases the probability of failure. Also, the age of equipment is important: the older the equipment, the higher the failure rate.

How do we discover the time that maintenance is due, and the age? The equipment statechart does not keep that information; when maintenance is done, it just comes to the **Working** state.

The easiest way of always be able to find out the time since a certain event is to *remember the time of the event occurrence in a variable*.

So, we will add two variables to the **EquipmentUnit** agent: **TimeLastMaintenance** and **TimeLastReplacement**. The type of these variables will be **double** because model time in AnyLogic has type **double**. What should the initial values of the variables be? The problem statement says nothing about the initial condition of the equipment, so let us assume that:

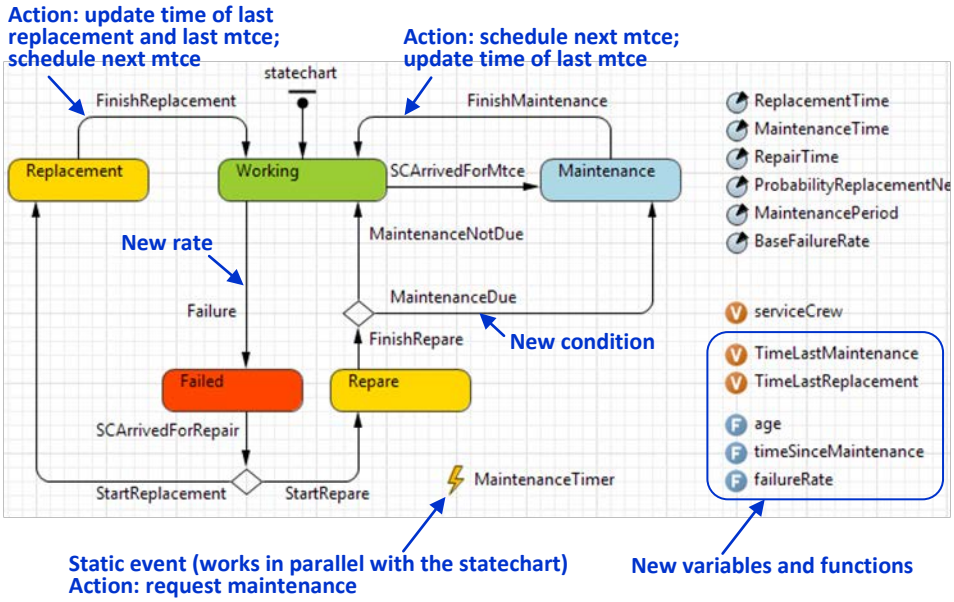
- No maintenance is overdue, and the time to the next maintenance is distributed uniformly across the equipment units from 0 to the maintenance period.
- The age is also distributed uniformly from 0 (new) to 3 maintenance periods (moderately old).

Given that the model time at the beginning of the simulation is 0 (the *calendar date* at time 0 can be anything we want), the initial values of the variables will be:

- **TimeLastMaintenance** is initialized as **uniform(-MaintenancePeriod, 0)**
- **TimeLastReplacement** is initially equal to **uniform(-3*MaintenancePeriod, 0)**

We will also write two useful auxiliary functions calculating age and time since last maintenance. **age()** is calculated as **time() – TimeLastReplacement** (in AnyLogic, **time()** is the current model time). Similarly, **timeSinceMaintenance()** returns **time() - TimeLastMaintenance**.

Both functions will return time intervals measured in the time units of the model, and it makes sense to set the time units to **days** (this is done in the properties of the model – the top level item in the **Projects** tree).



Changes in the EquipmentUnit agent: maintenance, age, and failure rate

Since now we know the age and the maintenance state of the equipment, we can properly calculate the failure rate, which depends on both things (as you may remember, in the first version of the model we just used the base failure rate). We were not given the exact dependency formula or any data to fit, so we will assume some simple dependency. For example:

- If maintenance is overdue, the increase of the failure rate is proportional to the overdue period divided by the maintenance period. For example, if the

maintenance has not been done for 180 days (it is 90 days overdue), the failure rate will be multiplied by 2.

- Similarly, the equipment older than 3 maintenance periods has the failure rate increased by the age divided by 3 maintenance periods.

This is the code of the **failureRate** function:

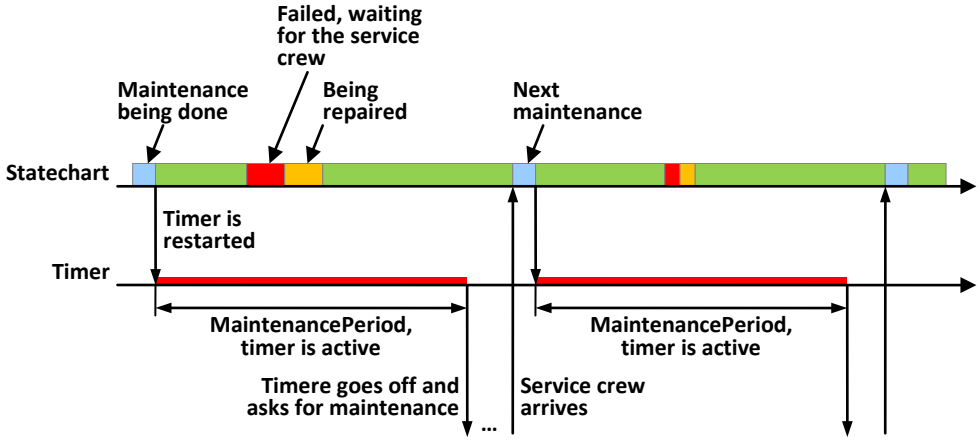
```
double mtceoverduefactor = max( 1, timeSinceMaintenance() / MaintenancePeriod );
double agefactor = max( 1, age() / ( 3 * MaintenancePeriod ) );
return BaseFailureRate * mtceoverduefactor * agefactor;
```

Now we can use this function in the rate of the **Failure** transition. Also, we can now write the proper condition of the transition branch **MaintenanceDue**; it will be **timeSinceMaintenance() > MaintenancePeriod**. The changes made to the model in this and the next section are highlighted in the Figure.

Scheduling maintenance. Handling requests of two types

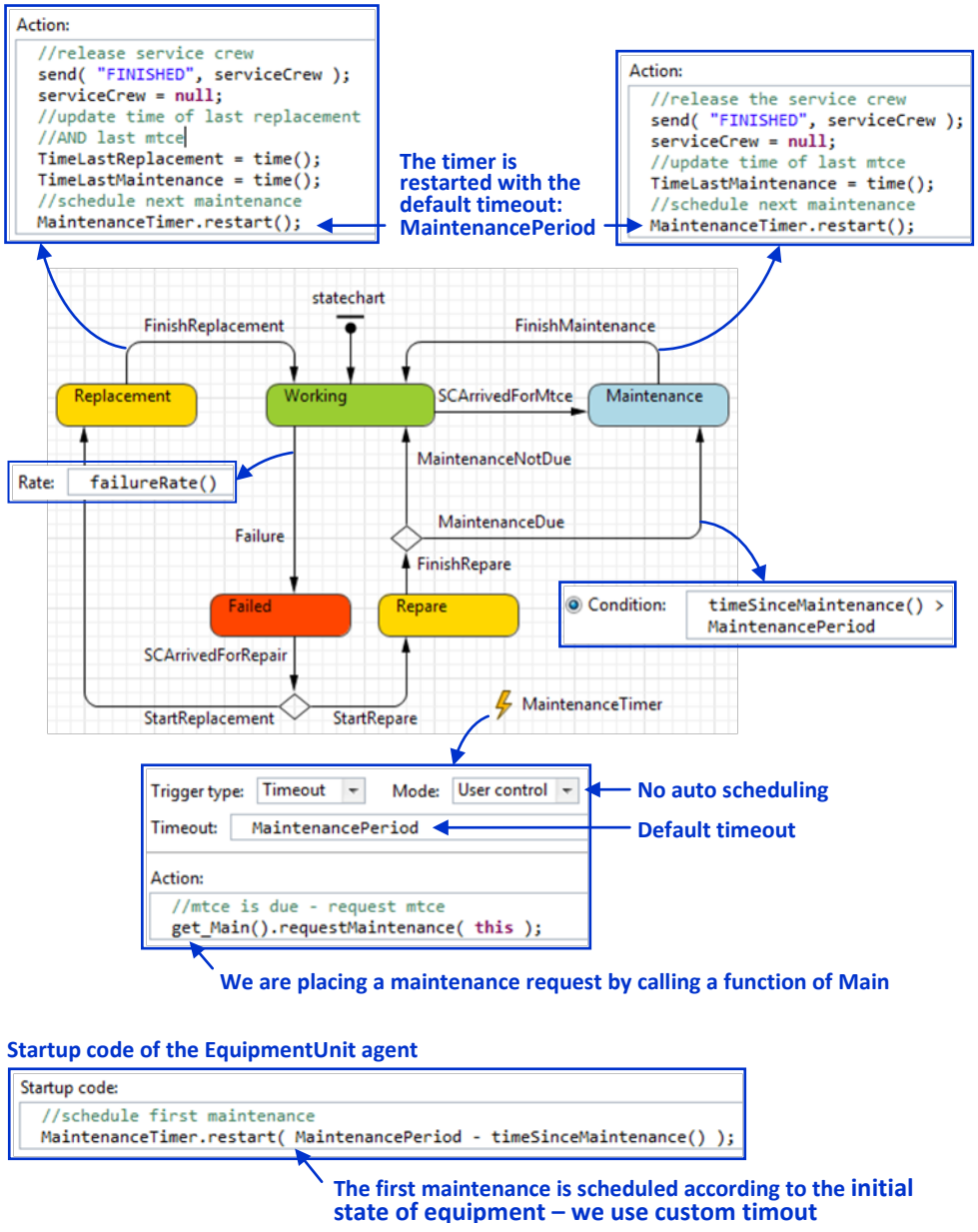
Our model is still missing the maintenance scheduling. Which object in the model should take care of that? In the real world, it is most likely the service system that keeps the log of completed maintenances and schedules the next ones. We could literally mirror this in the model by adding an array of dynamic events, one for each equipment unit, at the **Main** level. However, it would be more natural and elegant to have a static event in each equipment unit. The event will act like a timer.

The equipment unit has a statechart that defines the main behavior pattern. Now we are adding a small primitive activity (an event) that will go on *in parallel* to the main activity and interact with it, see the message sequence diagram in the Figure.



Two parallel activities in the EquipmentUnit agent: statechart and timer

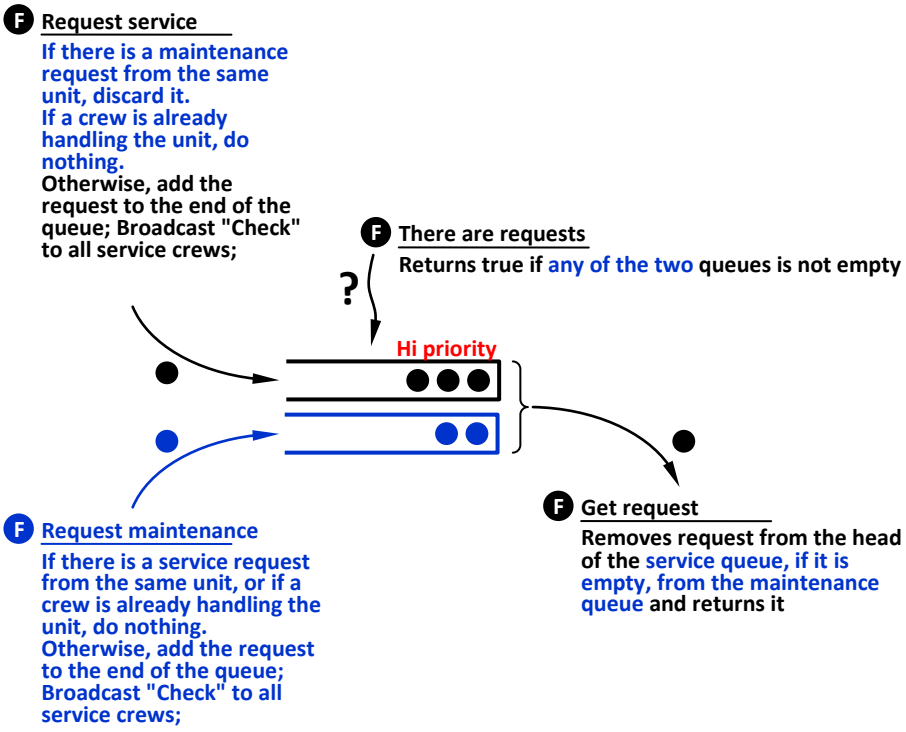
We will call the event **MaintenanceTimer**. The timer will be restarted each time the maintenance is done for the **MaintenancePeriod**. And we need to initialize the timer at the beginning of the simulation according to the initial value of the **TimeLastMaintenance** variable. The corresponding settings of the model are shown in the Figure.



Startup code of the EquipmentUnit agent

Properties of objects related to maintenance scheduling

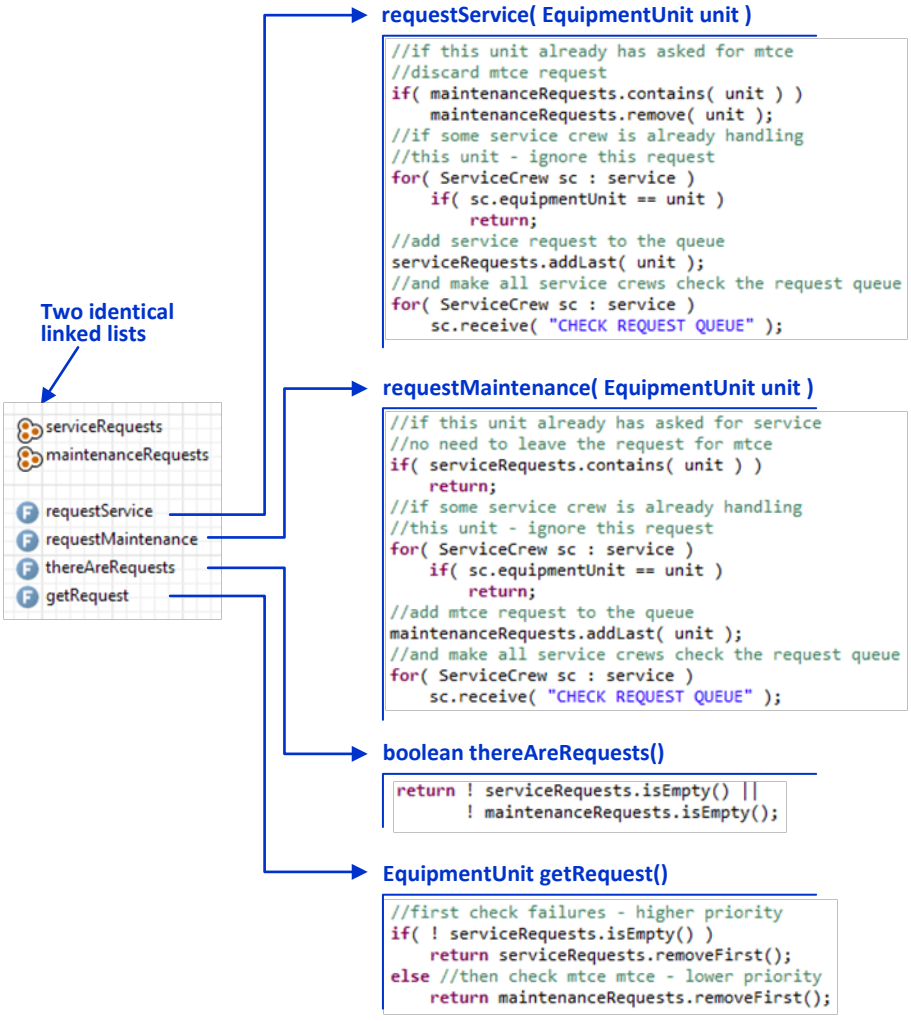
When the maintenance timer goes off, the equipment unit will request a service crew to come and perform the maintenance by calling the function **requestMaintenance()** of the **Main** object. That function still is to be implemented; so far, in the **Main** object, we only have one request queue and one function **requestService()** that puts the request there. Should we place the maintenance requests in the same queue? If we decide to do so (and leave the reference to the equipment unit as the request type), the requests will be indistinguishable and we will not be able to treat them differently; for example, to implement priorities. There are a couple options. Option one is to create a special type for a request that will include the reference to the equipment unit, the type of request (repair or maintenance), and maybe more information, such as timestamp. Option two is to have two different queues for equipment units that need repair and those that need maintenance. For simplicity's sake, we will choose the second option.



The "service dispatcher" in Main that handles two types of requests

The updated implementation of the "service dispatcher" is shown in the Figure. We will assume that service requests are treated as high priorities because the failed equipment stops bringing revenue. The maintenance requests are served only if there is no failed equipment.

The equipment unit, however, can generate two requests in parallel. For example, it can request maintenance and, while waiting for the service crew, it can fail and ask for repair. Or, the maintenance timer can go off while the equipment is being repaired. These situations need special treatment, because we do not want two service crews to arrive at the same equipment unit. Therefore, before adding a request to a queue, we are checking if the there was another request from the same unit. The code of the corresponding functions of **Main** is shown in the Figure.



The updated implementation of the service system in Main

Now the model functionality is completed and we can run the model again to check if equipment maintenance is done. You can see the number of maintenance requests in

the queue in the **Main** object, the time to the next maintenance nearby the **MaintenanceTimer** in **EquipmentUnit**, and the equipment statechart periodically entering the **Maintenance** state.

Discussion. Code in the model

As you can see, we have used some code. The code was needed for:

- Calculation of the equipment failure rate.
- Interaction of the statechart and the timer in the **EquipmentUnit** agent.
- Communication of the "service dispatcher" in **Main** and the service crews.
- Queue management in **Main**.

In the case of the failure rate, we had a complex relationship between variables originally described in an *algorithmic manner*: "if the equipment is older X then the failure rate increases by the age divided by X". Such a relationship is naturally implemented by code, and you will find code like this in simulation models of any kind. The code includes declaration of auxiliary variables and arithmetic calculations, sometimes conditional. For example:

- **double agefactor = max(1, age() / (3 * MaintenancePeriod));** – this code line declares a local variable **agefactor**, calculates the expression **age() / (3*MaintenancePeriod)**, and assigns its value to the variable if it is greater than 1; otherwise, it assigns 1.

The queue management code has a similar nature. The rules like "if a request is being added to the service queue, delete a request from the same equipment unit in the maintenance queue if there is any" are also best expressed in code. As long as we use linked lists for queues, we use the methods of Java collections. For example:

- **boolean contains(** *<element type>* **element)** – returns true if the collection contains the **element** and false otherwise.
- **remove(***<element type>* **element)** – removes the **element** from the collection.
- **addLast(** *<element type>* **element)** – adds the **element** to the end of the linked list.

The other two cases (interaction of the statechart and the timer and communication of **Main** and **ServiceCrew**) are typical for agent based modeling.

In agent based models, code is frequently used to link things that are not linked graphically. In particular, it is used to implement agent-to-agent and agent-to-environment communication, and to co-ordinate different activities within a single agent.

These are the examples of such code:

- The statement **MaintenanceTimer.restart()** written in the action code of a statechart transition addresses the static event **MaintenanceTimer** located in the same agent.
- The statement **get_Main().requestMaintenance()** in the action code of the **MaintenanceTimer** located in the **EquipmentUnit** agent reaches out to the equipment's container object **Main** and calls its function **requestMaintenence()**.
- The loop statement in **Main**

  ```
  for( ServiceCrew sc : service )
    if( sc.equipmentUnit == unit )
      return;
  ```

  iterates through all **ServiceCrew** agents embedded in **Main** (**service** is the name of the service crew collection), checks if the variable **equipmentUnit** in the service crew equals a given **unit**, and, if yes, exits the loop and the function where the loop is located.

The code patterns we considered are very typical and cover about 90% of the modeler's needs. For further information on how to write code and what can be done by code, we refer you to the chapter Java for AnyLogic users.

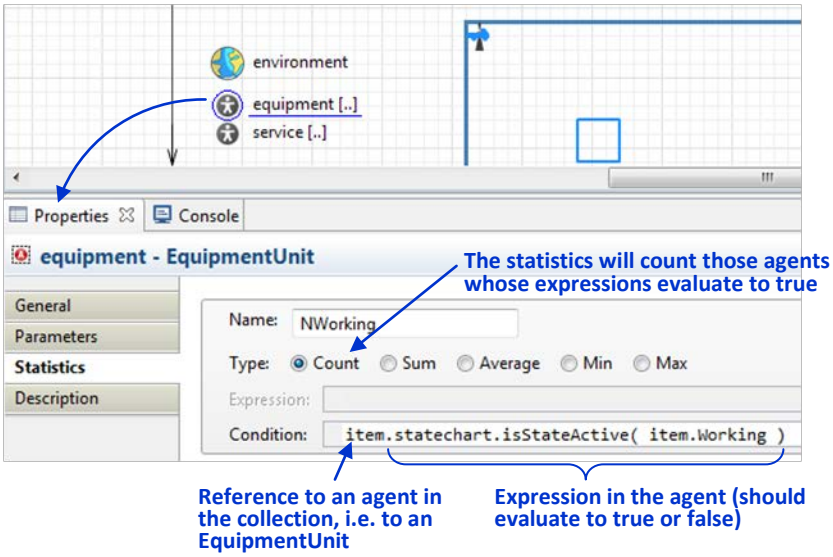
Phase 4. Model output. Statistics. Cost and revenue calculation

Now that the functionality is in place, we can work on the model output. So far, animation is the only output the model generates. In this design phase, we will add revenue and cost calculations throughout the model, and collect and visualize statistics. These are the output metrics we are interested in:

- Equipment availability
- Service crew utilization
- Cost of the service system
- Revenue

Equipment availability and service crew utilization

Both the equipment and the service crews are agents, so the task of calculating availability and utilization is the task of obtaining percentages and average numbers across the collections of agents. In AnyLogic, such statistics can be defined on the **Statistics** page of the agent collection properties, see the Figure.



Statistics defined in the collection of the equipment units

In those statistics we are counting the working equipment units, i.e. the units where the current statechart state is **Working**. The expression in **Condition,** filed, looks a bit unusual: the "natural" or "expected" form of the expression would be something like **statechart.isStateActive(Working)**. To understand why you should write the expression this way consider the Java code generated by AnyLogic for the statistics (the user's part of the code is highlighted):

```
int count = 0;
for( EquipmentUnit item : equipment ) {
  if( item.statechart.isStateActive( item.Working )
    count++;
}
```

We are currently in the **Main** object and *outside* the **EquipmentUnit** object. Therefore, according to Java rules, every function or variable inside **EquipmentUnit** must be *prefixed by the reference to the object*. The local variable **item** in the loop is the reference to the equipment unit, so it is put in front of the statechart and the state names.

You may also wonder why we did not select the statistics type **Average**. Average calculates the average of a numeric value across the collection. For example, if we were calculating the average age of the equipment, we would use type **Average**. The working / not working status of the equipment is a **boolean** value, so we are counting the working units.

The result of the statistics definition is the function **NWorking()** in the **Main** object that returns the number of working units at the time it is called. Similarly, we will define three other statistics functions:

- **NOnService()** calculating the number of equipment units being repaired or replaced with a slightly more complex condition:
  item.statechart.isStateActive(item.Repare) ||
  item.statechart.isStateActive(item.Replacement)
- **NOnMaintenance()** with the condition
  item.statechart.isStateActive(item.Maintenance)
- **NFailed()** with **item.statechart.isStateActive(item.Failed)**

So far, we have only prepared the tools to collect data; no data has actually been collected. We will now add a time stack chart to view the equipment availability.

The stack chart settings are shown in the Figure. There are four stripes in the chart, corresponding to the four different statistics we have defined. The colors of the stripes are the same as the colors of the equipment statechart states.

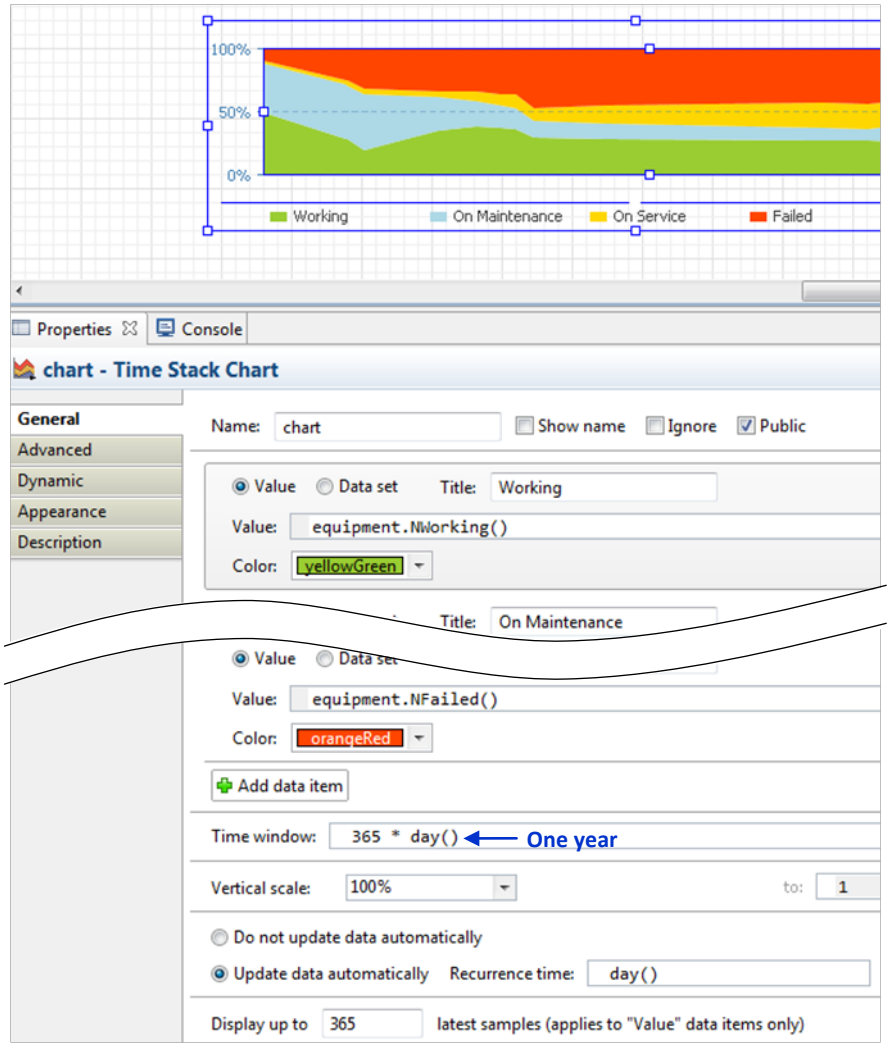
In the first version, the chart will display a time interval of one year (see the **Time window** property). Once per day (**Recurrence time** setting) it will evaluate all four data items (call the four statistics functions), and will internally keep a dataset of 365 latest samples (**Display up to** setting).

As long as the total number of equipment units is constant and we are interested in the percent of working units, the **Vertical scale** is set to 100%. This means that the total height of the four stripes will always equal the full height of the chart.

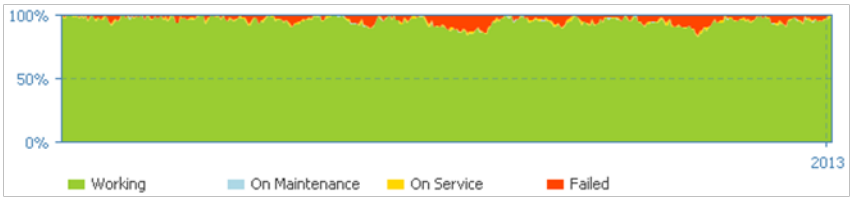
In most cases, it makes sense to separate the animation and output screens. Moreover, the amount of output data may require more than one screen. Use AnyLogic view areas to markup the screens and hyperlinks to switch between them.

The runtime picture of the chart after one year is shown at the bottom of the Figure. Not surprisingly, the percent of time spent on service and maintenance times is minor compared to the time equipment is up and running. But the time the equipment is failed and waits for the service crew (the red stripe) is significant.

This chart is good as a first iteration of our model output design. However, the chosen time window of one year is too short to see the effect of a service policy change, given the order of magnitude of the maintenance period and the impact of age on the failure rate. The sample period (once per day) may, on the contrary, be too long compared to the maintenance and repair times. The last problem with the chart is the noise that hides the possible "tides" in the system.



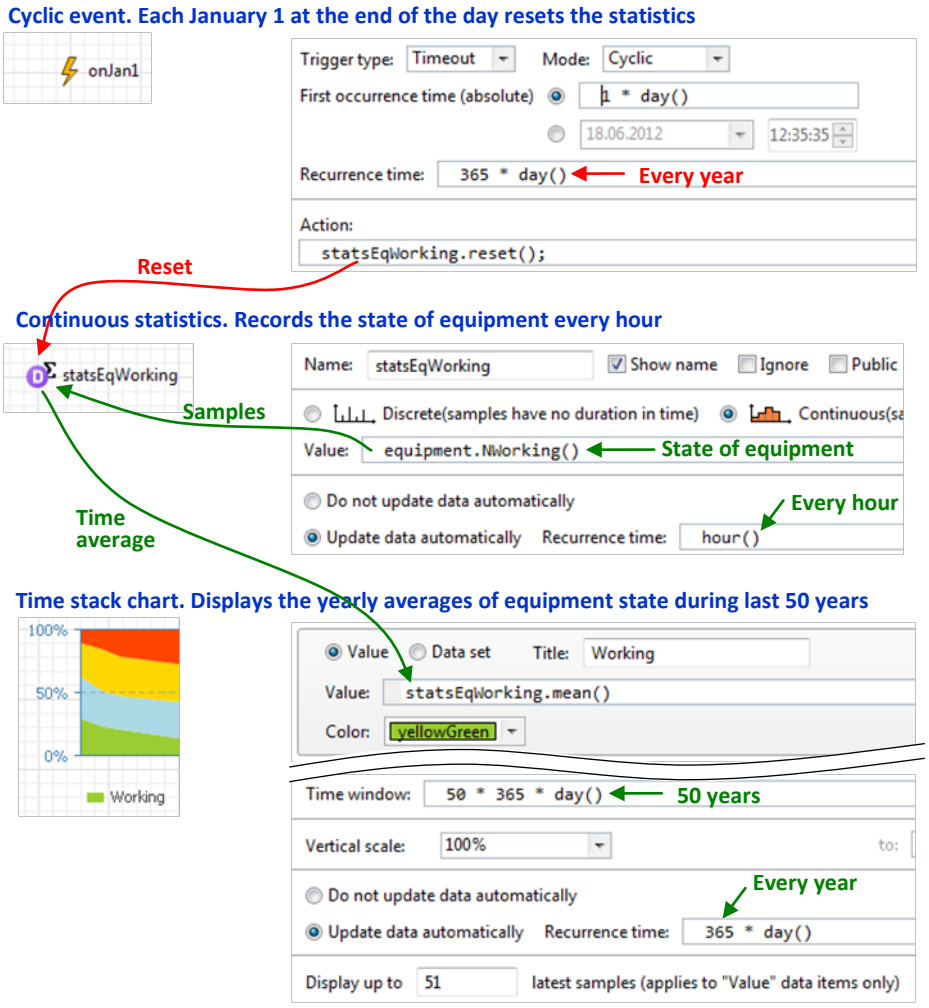
The chart at runtime after one year has been simulated



Time stack chart for equipment availability. Design time settings and runtime view

We will now modify the statistics collection and visualization to handle these issues. We will:

- Use a higher sampling rate (once per hour) to better monitor the state of the equipment.
- Accumulate the *time averages* of the equipment states during a year.
- Display annual averages in the same stack chart to see the 50 years' interval.

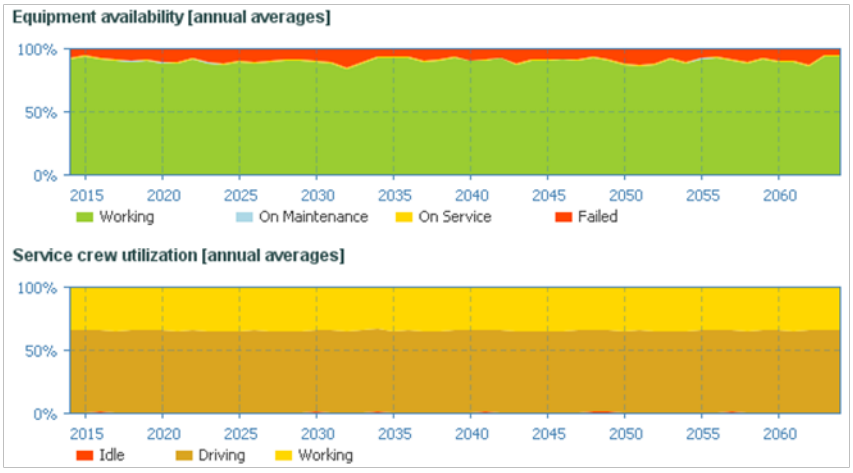


Statistics defined in the collection of the equipment units

The element of AnyLogic that is capable of calculating time averages is called continuous statistics. To create continuous statistics, you should drag the **Statistics** object from the **Analysis** palette and select **Continuous (samples have duration in time)** in its

properties. Every hour, we will add the number of working equipment units to the statistics. By the end of the year (at the end of the last day of a year) the statistics will have the full history of the equipment state, and we will add the time average (the function **mean()** of the statistics) to the stack chart, see the Figure. The day after, we will reset the statistics so that it starts collecting data for the next year. This is done by the cyclic event **onJan1** that is set up to occur at the end of the 1st day, 366th day, etc.

In the same manner, we will define the statistics for the on maintenance, on service, and failed states of equipment, and for the idle, driving, and working states of the service crews. The two stack charts with the results of 50 simulated years with default parameter values are shown in the Figure. These charts (along with the financial ones that we will add in the next section) will be the basis for our policy analysis.



Annual averages of equipment and service states during a 50 years period

Cost and revenue

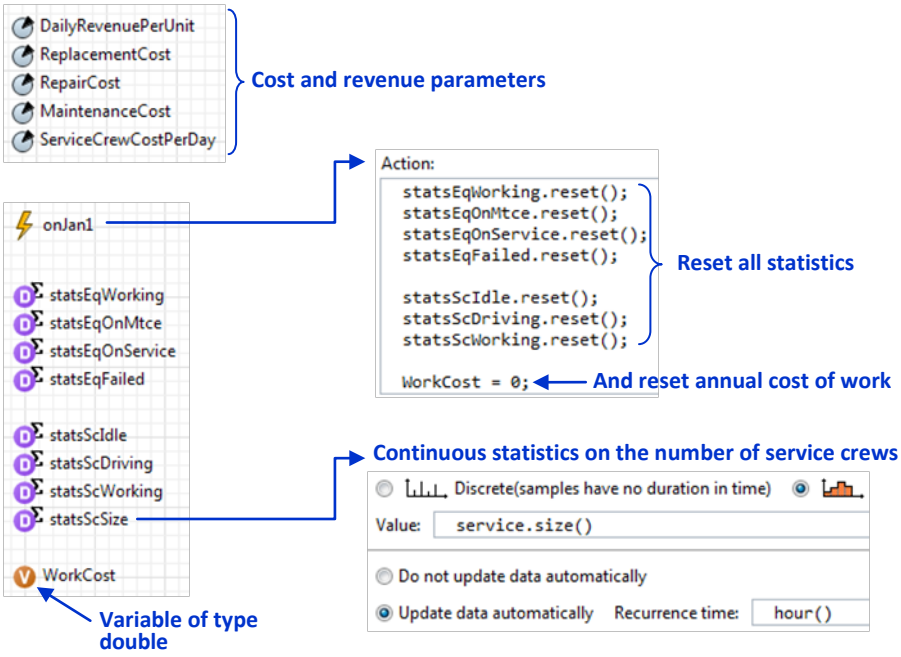
How do we calculate the cost of our service system? There are two components of cost:

- Daily cost of "employing" the service crews, and
- Per-operation cost of maintenance, repair, and replacement.

The first part of the cost equals (the number of service crews) x (daily cost of a crew) x (365). Potentially, we may want to vary the number of service crews during a year, so we will use the time average number (yet another continuous statistics will be needed).

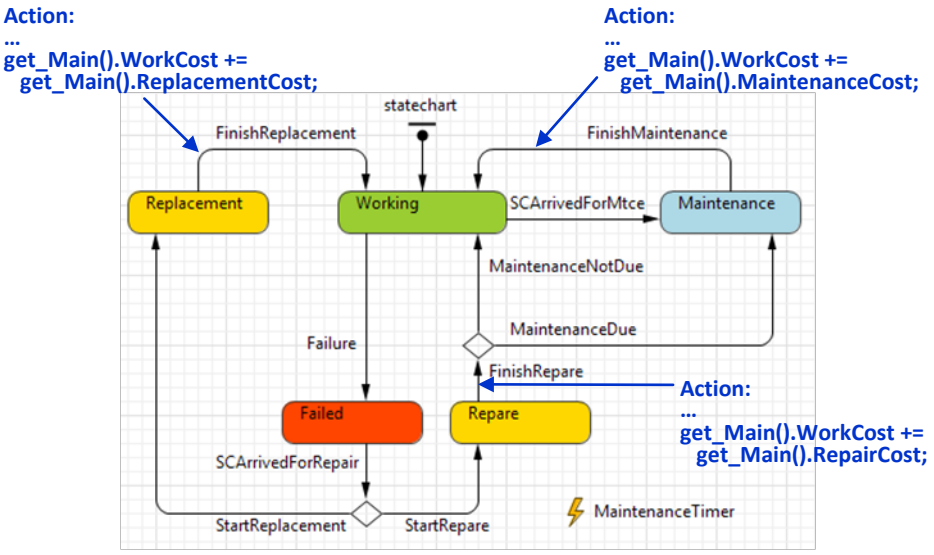
As for the cost of operations being performed, the information is currently not recorded anywhere. We will create a variable **WorkCost** at the top level in **Main** and

increment it each time a maintenance, repair, or replacement operation is performed. In addition, we will create the cost and revenue parameters in the **Main** object. The changes made to **Main** are shown in the Figure.



Elements in Main related to cost and revenue calculations

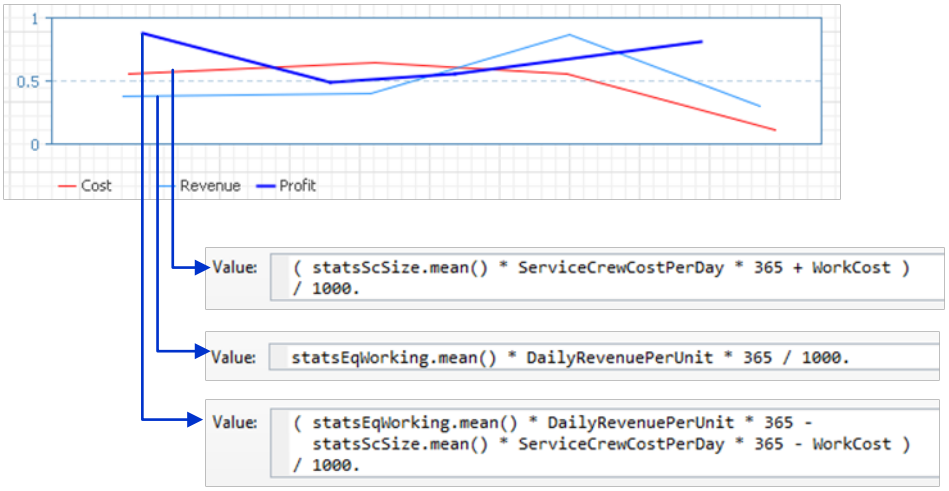
In the **EquipmentUnit** agent we will include the increments of the **WorkCost** variable at the end of each operation. The corresponding actions are added to the transitions **FinishMaintenance**, **FinishRepair**, and **FinishReplacement**, see the Figure. As long as both the cost parameters and the variable **WorkCost** are located in **Main**, we need to use the prefix **get_Main()** to access them from the equipment unit.



EquipmentUnit statechart updated to calculate the cost of operations

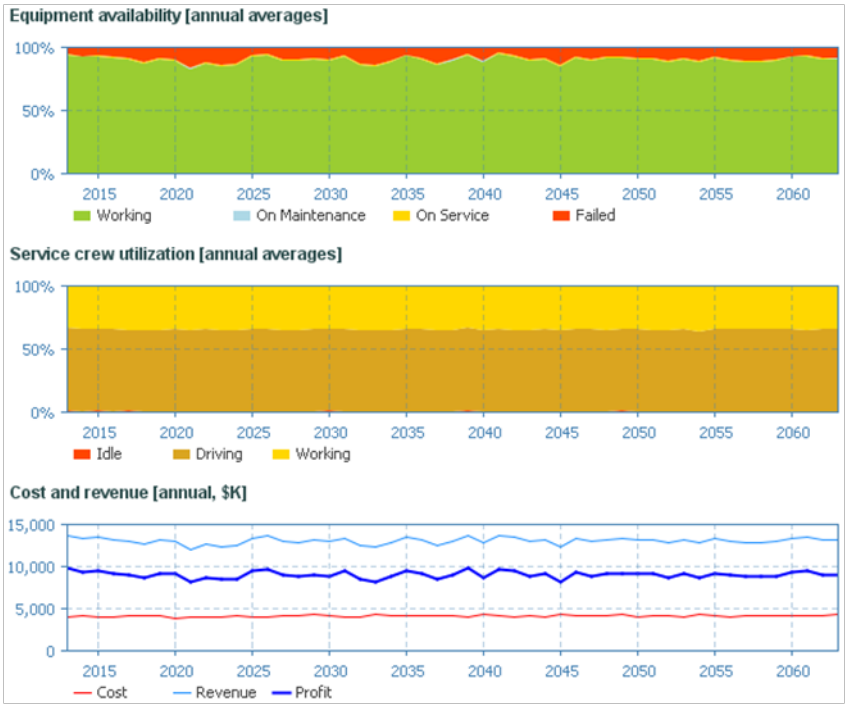
Revenue calculation is easy. A working equipment unit is bringing **DailyRevenuePerUnit** dollars per day. Therefore, the annual revenue can be calculated as **statsEqWorking.mean() * DailyRevenuePerUnit * 365**.

Finally, we will create a chart of annual cost, revenue, and profit. We will use a time plot, see the Figure. The time window, recurrence, and history size settings are the same as in the time stack charts we created before. To keep the numbers smaller, we will display them in thousands dollars (all values are divided by 1000).



Cost and revenue chart

We have completed the measurements, statistics, and output visualization for our model. The resulting output screen is shown in the Figure.



The model output screen with cost and revenue. 50 years simulated

Phase 5. Control panel. Running the flight simulator

We will now convert our model into a flight simulator where parameters and policies can be varied on the fly and the results are displayed immediately. The model user will be able to vary two things:

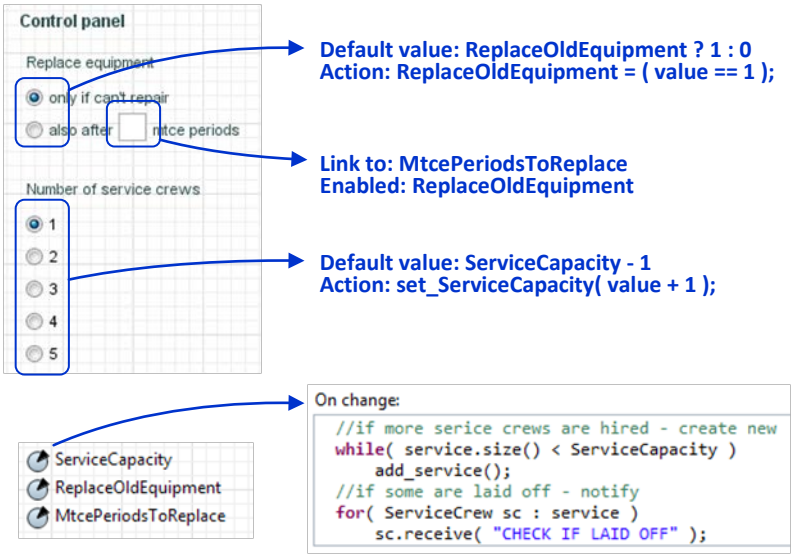
- The number of service crews, and
- The replacement policy, namely: a) replace only failed equipment that cannot be repaired, or b) also replace equipment after N maintenance periods, even if it is still working

Design of control panel

We will create a simple control panel with two groups of radio buttons and one edit box, see the figure. We will need three more parameters in the model:

- **ServiceCapacity** –the number of service crews, integer type, initially 3.

- **ReplaceOldEquipment** – boolean, initially false, if true, the equipment is replaced after **MtcePeriodToReplace** maintenance periods.
- **MtcePeriodToReplace** – integer, initially 5, the maximum age of equipment if the **ReplaceOldEquipment** policy applies.



The model control panel and related parameters

The value of a radio button control is a 0-based integer. Therefore, if the user selects **Replace equipment only if can't repair**, the value is 0, and the boolean parameter **ReplaceOldEquipment** is set to **(value == 1)**, which evaluates to **false**. The edit box is linked to an integer parameter, so it will automatically accept only an integer input.

Now we need to set up the model to properly react to the policy changes made on the fly.

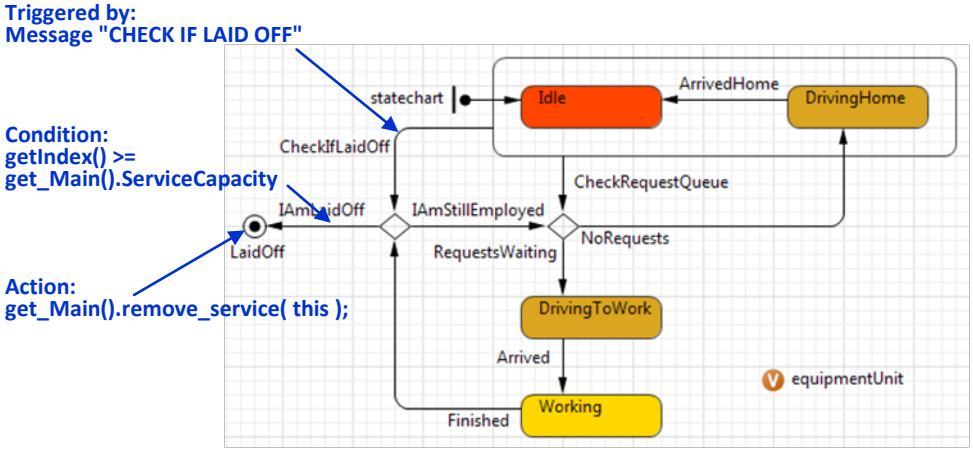
Changing the number of service crews

In AnyLogic, agents can be added or deleted to or from a collection by calling the functions **add_*<collection_name>*()** and **remove_*<collection name>*(agent)**. To add a new service crew to our service system, we can simply call **add_service()**. However, we *cannot delete a service crew at an arbitrary moment of time*: the crew can be handling a service request and, if the crew is deleted in the middle of say, a repair operation, the operation will not finish correctly. For example, the message **"FINISHED"** will be sent to a non-existing agent. To delete a service crew correctly, we first need to make sure it is idle.

Here you can see the difference with discrete event (process-based) modeling. In a discrete event model you typically can reduce the number of resources in a pool at any time and, if the resource being deleted is busy, it will follow some default policy; for example, finish the work and then disappear. In the agent based model, we are implementing this policy explicitly.

Our implementation will be the following. Each agent in a collection has an index (from 0 to the size of the collection - 1), and we will use that index to check if the service crew is still employed. Each time a service crew finishes work with equipment, it will check if its index is greater or equal than the parameter **ServiceCapacity**. If yes, it will immediately delete itself. And for those service crews that are idle or driving home, we will send a special notification to make check the same condition.

Part of this scheme is implemented in **Main** in the **On change** code of the parameter **ServiceCapacity**, see the Figure. The second part is implemented in the updated **ServiceCrew** agent, see the Figure. The decision diamond on the left has two entries: the **Finished** transition and the **CheckIfLaidOff** transition, and two outgoing branches: one leads back to the normal operation, and another to the final state, where the agent deletes itself (**this** is the Java reference to self).

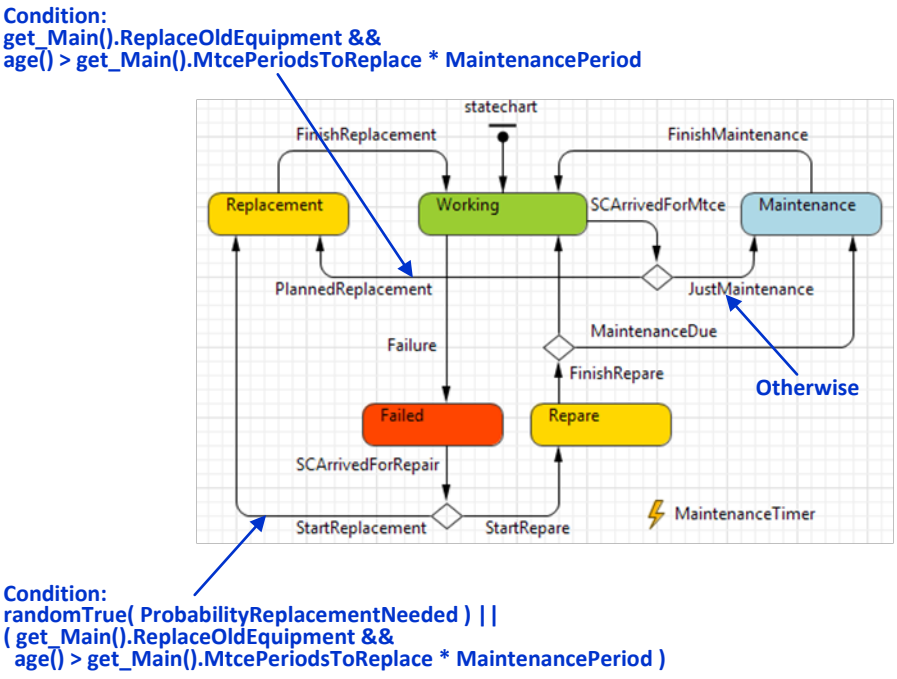


The ServiceCrew statechart updated to react to the service capacity changes

Equipment replacement policy

We need to implement the optional replacement of the equipment after a given number of maintenance periods. We already have **ReplaceOldEquipment** and **MtcePeriodsTpReplace** parameters in **Main**. The rest can be naturally done in the **EquipmentUnit** agent. Each time the service crew visits the equipment unit, we will check if the policy is active; if yes, we will compare the age of the equipment with

MtcePeriodsToReplace * MaintenancePeriod. If the age is greater, the crew will perform the "planned" replacement of the working equipment.



The EquipmentUnit statechart implementing the optional replacement policy

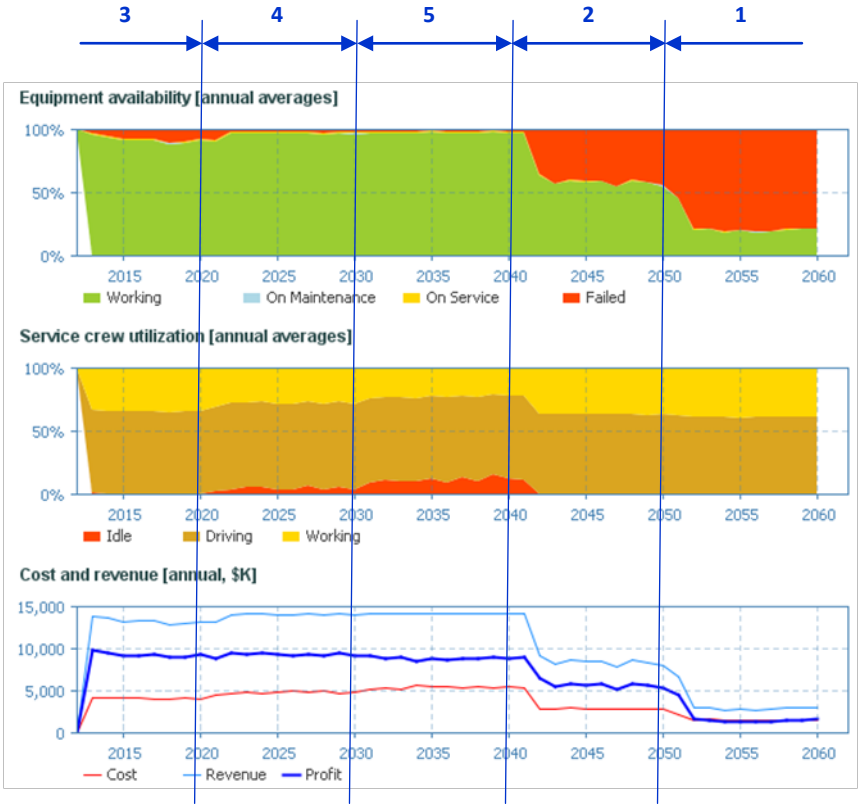
We added another decision diamond after the transition **SCArrivedForMtce** ("service crew arrived for maintenance"). If a planned replacement is recommended and due, the statechart proceeds directly to the **Replacement** state. We also modified the condition of the **StartRepare** branch. Now, if the service crew comes to fix the failed equipment, it would also check if the planned replacement needs to be done.

The model now is ready for experiments.

Running the flight simulator

In the first experiment, we will vary the number of service crews. The results are shown in the Figure. The profit is virtually the same with four crews as with three, but the equipment availability is considerably higher with four crews. The further increase of the service capacity does not result in a noticeable increase of availability, but it lowers the profit. Less than three service crews cannot handle the fleet of 100 equipment units.

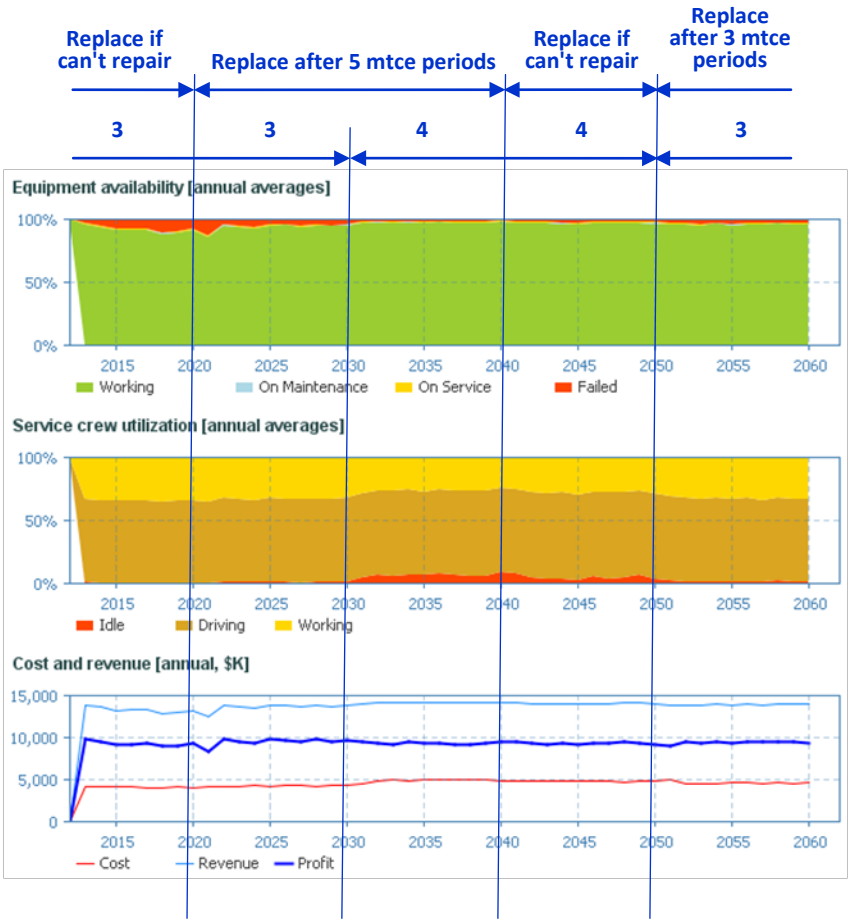
While, in reality, the system we are modeling will never remain unchanged for 50 years, the 50 years' time window is good for the flight simulator mode as it allows us to compare different solutions on one chart.



Trying different numbers of service crews

In the next run of our flight simulator, we will try three and four service crews and vary the equipment replacement policy. The results (see the Figure) show that three service crews can successfully maintain high equipment availability and, at the same time, bring high profit if old equipment is replaced.

Should we also try two service crews? We can, but even with the three parameters we can vary (the number of service crews, the active/inactive policy, and the maximum allowed age of equipment) it is quite hard to manually explore the parameter space. Our next step will be to submit this task to the automatic optimizer.



Trying 3 and 4 service crews with different replacement policies

Phase 6. Using the optimizer to find the best solution

We will use the OptQuest™ optimizer that is embedded into AnyLogic. Being a metaheuristic optimizer, OptQuest treats the simulation model as a black box and can work with models of any kind, be they discrete event, agent based, or system dynamics models. It is also capable of working with stochastic models and performing optimization under uncertainty.

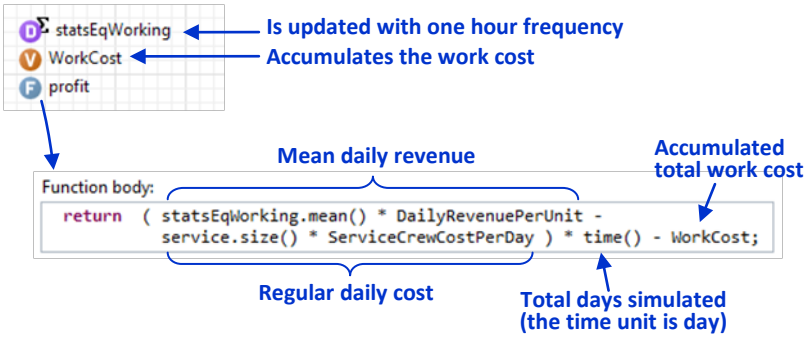
Preparing the model for optimization

Before creating the optimization experiment, we need to prepare the model. During optimization, we are not interested in animation and visualization of the statistics. We are, however, interested in performing simulation runs as fast as possible, because

there will be many of them. As to the animation graphics and the controls, we can either delete them or leave them as-is; when not shown on the screen, AnyLogic animation does not consume any computational resources. Charts and statistics elements, however, are set up to evaluate their values with a certain frequency, which slows down the simulation (especially when evaluating a value requires iteration over a collection of agents). Therefore, we will delete:

- All charts.
- All statistics except for **statsEqWorking**, which is needed to calculate the revenue.
- Event **onJan1** that resets the statistics every year.

We will create a new function **profit()** that will be called once at the end of a simulation run and calculate the cumulative profit. This will be our objective function. The Figure shows what is left.



The statistics and the objective function needed for optimization

Setting up the optimization experiment

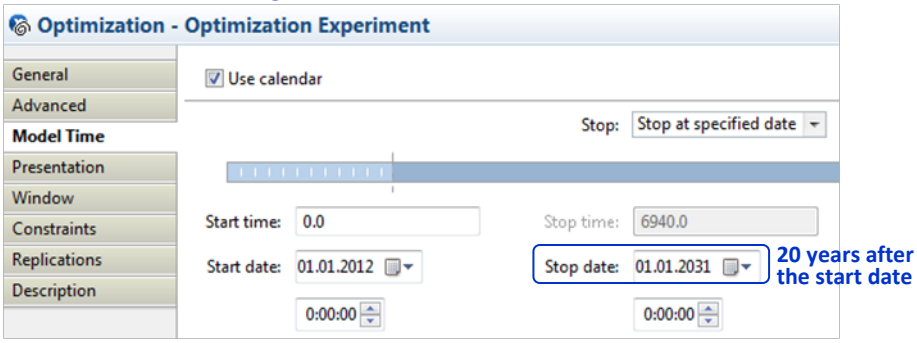
One of the important settings is the duration of a simulation run. The duration should be long enough to let the model work in the regular mode and produce meaningful output. The warm-up period, in our case, is not a big issue: we are initializing the equipment units at randomly distributed age and last maintenance dates, so the initial state of the model differs from a regular state only in the following:

- None of the equipment has failed or is being repaired.
- All service crews are idle and at their home location.
- The service and maintenance request queues are empty.

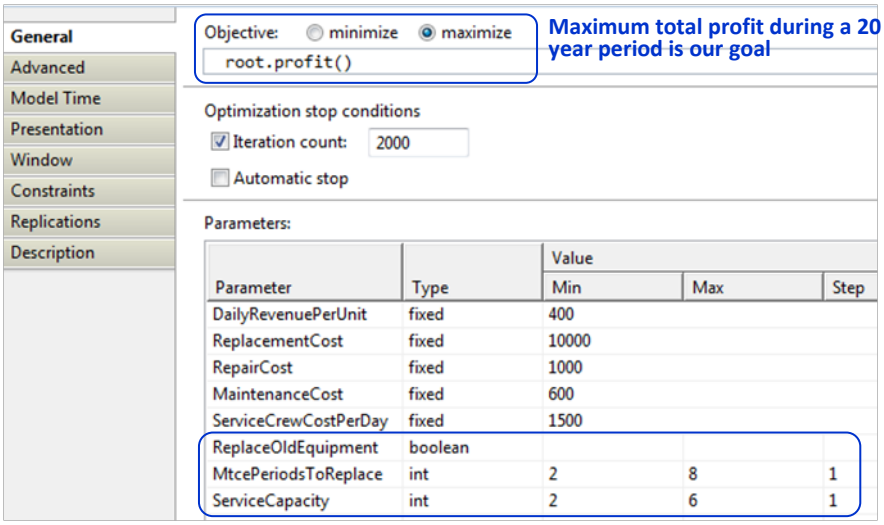
Given the failure rates and the maintenance period, the model should enter the regular mode in less than a year. We will set the duration of a run to 20 years and will not exclude the warm-up period from the output.

We will ask the optimizer to maximize the cumulative profit evaluated at the end of a simulation run, so we just write **root.profit()** in the objective function (**root** is the reference to the top-level object in the model, which in our case is **Main**).

Simulation duration settings

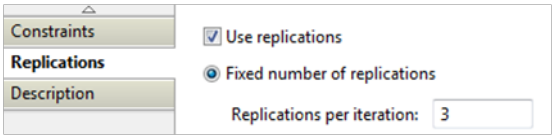


Objective and solution space settings



The optimizer will vary these three parameters

Stochastic optimization settings



Settings of the optimization experiment

The model has eight parameters at the top level **Main** object and more in the **EquipmentUnit** agent. The solution space, however, is limited to only three parameters

(all of them are in **Main**): **ServiceCapacity**, **ReplaceOldEquipment**, and **MtcePeriodsToReplace**. The solution space settings are shown in the Figure.

From the flight simulator runs, we remember that two or fewer service teams are not capable of handling the equipment, and five teams will be underutilized. Hence, the minimum and maximum values of the **ServiceCapacity** parameter. The range for the **MtcePeriodsToReplace** [2..8] is chosen both from the experience of the previous runs and from the knowledge of the failure rate function.

The last thing we need to set up is the number of replications. Our model is clearly stochastic and, given that the seed of the random number generator is chosen randomly, each run may produce a different output. Therefore, will perform multiple runs for each set of the input parameters (multiple replications) and use the distribution of the simulation output instead of a single value. A large number of replications obviously slows down the optimization, so we will set it to three.

The methodology for dealing with the model warm-up and for choosing the number of replications is outside the scope of this chapter and is well described, for example, in [???].

Optimization run

Now we can run the optimization. On the author's machine, the optimization was completed in about two minutes and produced the results shown in the Figure. The default user interface of the experiment was slightly modified. The chart on the right shows the progress of the optimization. Each dot in the chart corresponds to an iteration performed (each iteration has three runs, according to our replication settings). The vertical axis is the value of the objective function.

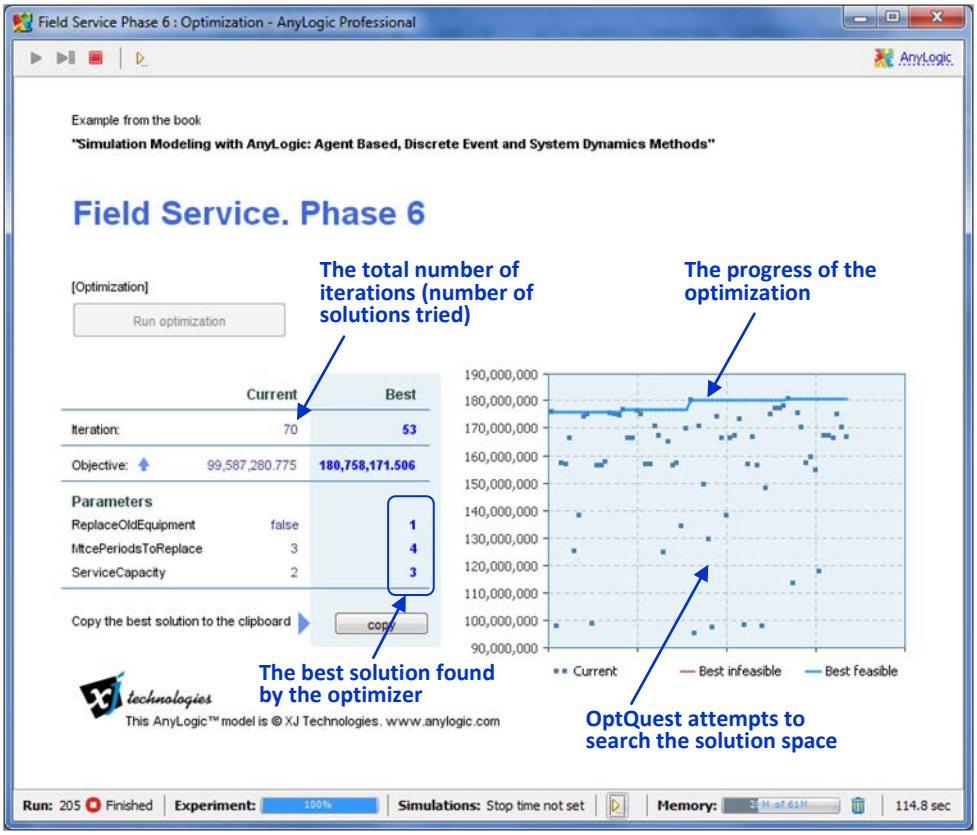
The best solution found by the optimizer is this:

The solution

- There are 3 service teams.
- We do replace old equipment, even if it works.
- The maximum allowed equipment age is 4 maintenance periods, i.e. one year.

Under these conditions, the estimated total 20-year profit is $180,758,172, which makes an average annual profit of $9,037,909 (the optimization experiment, however, does not tell us how the profit is distributed over the 20 years; to find that out, you can copy the best parameter values into a simulation experiment we created before and run it to see the charts).

The best parameter values (3 and 4) are in the middle of the searched ranges, which means that the ranges were, most likely, well chosen.



The statistics and the objective function needed for optimization

You may have noticed that, although the upper limit of the number of iterations was set to 2000, the optimizer only performed 70. This is because in our model, all three parameters are discrete and the solution space has only [2..8] * [2..6] * [true, false] = 70 points. The optimizer was able to *fully search the solution space* – a rare simple case.

We can, however, further reduce the number of iterations. Varying **MtcePeriodsToReplace** does not make any sense when the **ReplaceOldEquipment** policy is inactive. To pass this knowledge on to the optimizer you can use constraints – conditions on the input parameters that are tested *before a simulation run* and prevent the optimizer from trying particular solutions.

In AnyLogic, constraints are specified on the **Constraints** page of the optimization experiment properties in the form *<arithmetic expression over parameters> <relation> <bound>* where *<relation>* can be >=, <= or =. Boolean parameters in the constraint expressions take values 0 and 1.

Restricted solution space

MtcePeriodsToReplace \ ReplaceOldEquipment	0	1
2	yes	yes
3	no	yes
4	no	yes
5	no	yes
6	no	yes
7	no	yes
8	no	yes

Value of the constraint expression

MtcePeriodsToReplace \ ReplaceOldEquipment	0	1
2	2	-8
3	3	-7
4	4	-6
5	5	-5
6	6	-4
7	7	-3
8	8	-2

Constraint in AnyLogic

Constraints on simulation parameters (are tested before a simulation run):

Enabled	Expression	Type	Bound
☑	MtcePeriodsToReplace - 10 * ReplaceOldEquipment	<=	2.0

Optimization constraint

In our case, we need to invent an arithmetic expression that would be greater (or less) than a certain value for all meaningful combinations of the two parameters, see the Figure (when the replacement policy is inactive we just allow one arbitrary value of **MtcePeriodsToReplace**, say, 2). A possible expression that does the job is shown in the screenshot.

With that constraint enabled, the number of iterations reduces to 40 and the solution is found in 62.8 sec instead of 113.4 sec (on the author's machine with two cores).

Assumptions

We can now deliver the final results of the modeling project to our client. The deliverables, however, should always include the list of assumptions made by the modeler under which the results make sense.

In a properly performed project, each of those assumptions should have been discussed with the client and approved at the model design phases. Once again, we recommend involving the client in the project on all stages and making as many iterations with the client and getting as much feedback from the client as possible.

So, our major assumptions in this model are:

1. The formula for the equipment failure rate is one of our central assumptions, along with the exponentially distributed time between failures.

2. Repair, replacement, and maintenance times are triangularly distributed.
3. Repair, replacement, and maintenance have a fixed flat cost.
4. There are no roads in the area. Service crews drive in straight lines directly from origin to destination at a constant speed. The more correct formulation of this assumption is "the driving time is always proportional to the straight line distance from origin to destination".
5. There are no shifts or breaks. All service crews work 24 hours a day.
6. Service crews never fail and always have all necessary parts and tools on board. They never need to drive to the base location to pick up missing stuff.
7. Service crews do not optimize their routes. They just take the next request from the queue and drive there, whereas they could choose a request from a closest location.
8. Service crews are equipped with a radio and can take new assignments while driving.

Bonus phase. 3D animation

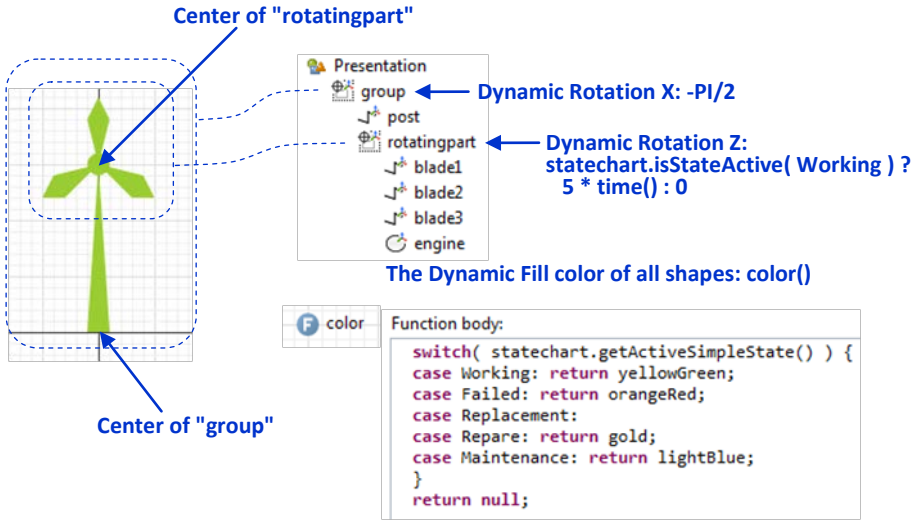
As a bonus to the work we have completed, we will build a 3D animation of the field service model. All things that happen in the model happen in 2D space. The goals of adding 3D are:

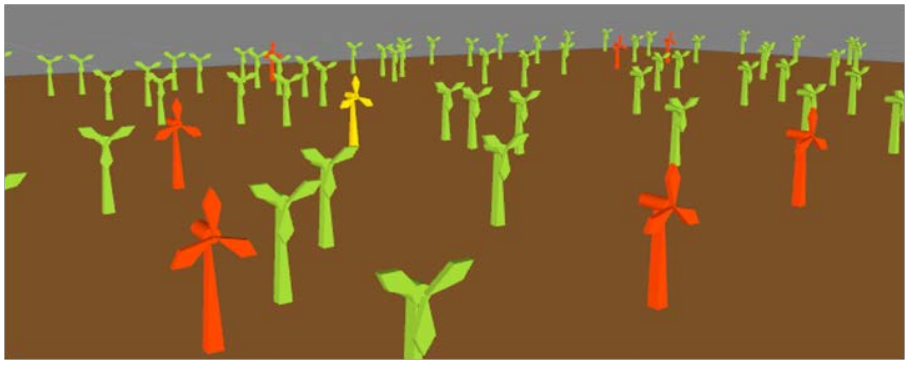
- To have fun.
- To make the model demonstration more entertaining and, sometimes, more convincing.
- To have a better debugging tool.

3D animation has one interesting advantage over 2D animation. With its perspective view, 3D animation is better suited for observing large areas. You can position the camera to have a detailed view of the current point of interest, and still be able to see the rest of the scene; the further the object is from the point of interest, the smaller it appears.

Adding the third dimension is easy. First, the group containing the equipment and service crew animations should be marked as shown in 3D (the **Show in 3D** property should be selected). We will use the framing rectangle as a ground, so it will get some fill color; its Z coordinate will be set to -1, and the Z-height – to 1. The **home** rectangle will be placed slightly above: Z = 1 and Z-height = 1. We will also create a 3D window and yet another view area for it. In total, we now have three views of the model: 2D, output, and 3D.

The animation of the equipment unit should also be marked as 3D. If you have used shapes not supported in 3D, you need to replace them with other shapes. For example, in our wind turbine picture, curves should be replaced by polylines. Also, we will rotate the picture by 90 degrees around the X axis to make it stand vertically in 3D (see also the example model Sign on two posts). To have more fun, we can make the blades rotate when the wind turbine is working. Lastly, we can use color to reflect the state of the equipment.





3D animation of the wind turbines

The shapes, groups and uses for the wind turbine animation and their properties are shown in the Figure. The Z coordinates and Z-heights of the shapes were adjusted. A new function **color()** was created in the **EquipmentUnit** agent. It returns the color reflecting the current state of the equipment, and is used in multiple dynamic **Fill color** fields of shapes.

If you run the model with these changes, you will notice that equipment animation is shown only in 3D windows; it has disappeared from the 2D animation. This is because the shapes are rotated 90 degrees around the X axis. To restore the 2D picture, we recommend you:

- Make a copy of the whole top-level group.
- Uncheck its **Show in 3D** property.
- Clear its dynamic **Rotation X** field.

Frequently, it makes sense to create separate animations for 2D and 3D views.

In the **ServiceCrew** agent, we will delete the flat 2D animation of the lorry and add a 3D object **Lorry** from the **3D objects** palette. The scale of the object may need to be adjusted to fit the scene. The 2D view will show the 2D projection of the lorry, which looks fine.

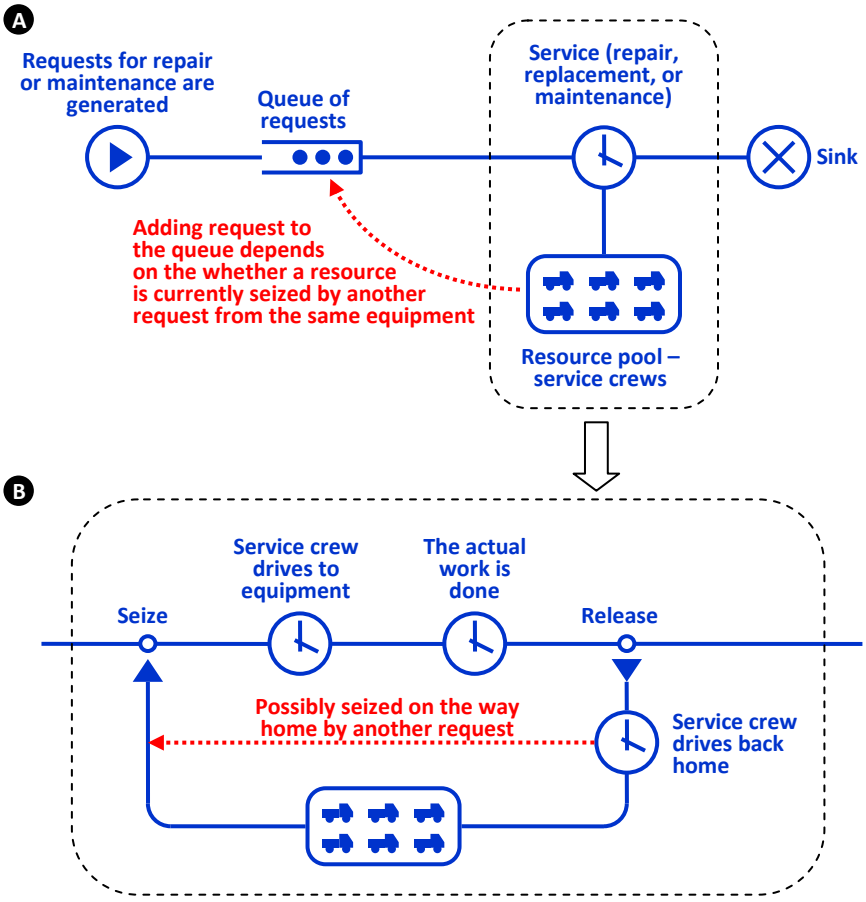
That's it! One thing you can do to improve the default 3D view is to choose a good viewpoint, copy its settings to a camera, and associate the camera with the 3D window (see the Cameras section of the 3D animation chapter).

3D an 2D animation of the Field service model

Bonus discussion. Could we model this in discrete event style?

Now that we have finished the model, some of you may ask: Why did we use the agent based approach? Couldn't we do the same model in the discrete event style with much less effort? Your doubts may be partially supported by the fact that the system we were modeling is a service system, a type which is known to map well to process-based flowchart languages. Let us consider a potential discrete-event model design for the same problem.

The top-level process flow is easy. We have an incoming stream of maintenance and repair requests (which are entities) that are serviced by a pool of service crews (which are resources). This is a classical source – queue – service – sink model, see the Figure A.



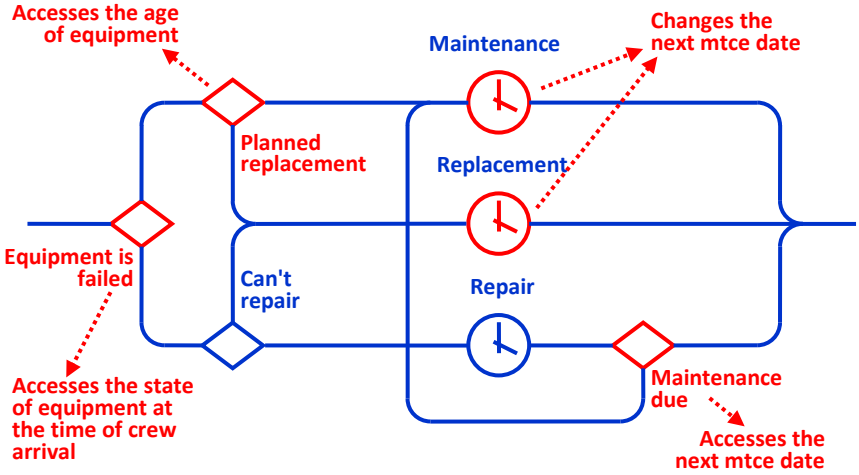
The top-level process flow and the "service" subprocess

We can have a single queue for both types of requests and treat repair requests as high priority (all discrete event tools support priority queues). The rule that "an incoming repair request discards a maintenance request from the same unit" can also be implemented, provided you have access to the queue elements and the ability to remove them. However, another rule that says "if a request comes in while a service crew is already handling the equipment, the request is ignored" could require some non-trivial coding in a discrete event model; we would have to either search all entities being serviced or iterate through all service crews to find out what are they doing.

In a discrete event model, implementation of the queuing policy would result in approximately as much code as in our agent based model. Some DE tools may not have the necessary API. However, priority queue is a standard block in DE tools.

The "service" sub-process includes seizing a resource (a service crew), waiting for the crew to arrive, the actual work, and releasing of the service crew, which then drives home, see the Figure B. There are DE tools that support mobile resources. The only thing that is rarely supported is "interception" of the resource on its way home to assign another task (the red arrow in the Figure B).

So far there are no *conceptual* problems with using the discrete event method, only potential technical limitations of some particular tools. But, we still have to consider the "work" block and the request generation.

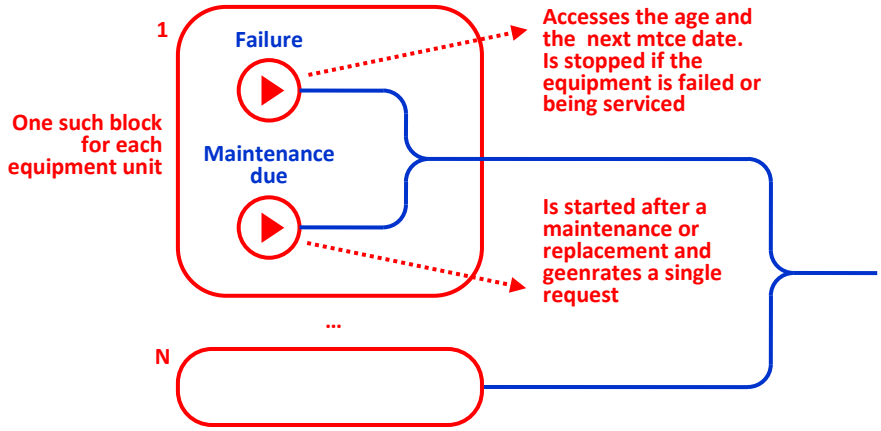


Subprocess "The actual work"

Once the crew arrives at the equipment unit, it may find the unit in different states. (Regardless of the request type: for example, while the unit was waiting for

maintenance, it could fail.) The work being done also depends on the age of the equipment and on the date of the next scheduled maintenance. Conditions in the flowchart decision blocks explicitly refer to the *state of the equipment*, and the actions modify the state, see the Figure.

The *state information*, therefore, should be stored for each equipment unit in a discrete event model anyway.



Generator of repair and maintenance requests

The request generation part is the most interesting part. It does not map to the discrete event methodology at all. First, we clearly need a separate generator for each equipment unit because the failure rate and the maintenance cycle are defined for a unit. Second, the streams of requests are irregular: the next failure is scheduled only after the equipment has been brought back to the working state, and the next maintenance is scheduled only after the current one is completed, or if the equipment has been replaced. The request sources work, therefore, in a very unnatural mode: they are partially controlled by the changes of the equipment state that are done elsewhere in the flowchart. *The flowchart gets cross-linked by code references and stops being a self-explanatory visual construct*.

No matter how hard we try to "package" this system into a process, we will inevitably end up with mimicking a set of independent objects having state information and state-dependent behavior. And for that, the discrete event modeling paradigm does not offer anything nearly as elegant as agents and statecharts.