An Introduction
to
SIMUL8 2005
Release 12

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for
Visual Thinking International
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1. BUILDING A SIMPLE SIMULATION MODEL WITH SIMUL8 2005

1.1 An introduction to building simulation models

1.1.1 What is SIMUL8?

SIMUL8 is a computer package for Discrete Event Simulation from Simul8 Corporation. It allows the user to create a visual model of the system being investigated by drawing *simulation objects/elements* directly on the screen. Typical objects may be work items, queues or service points. The work items may be physical entities such as manufactured goods which may be held in a storage area before being processed on a machine, or they may be ‘virtual work items’ such as telephone enquiries which are held in a queue before being processed by an operator.

When the system has been modelled then a simulation can be undertaken. The flow of work items around the system is shown by animation on the screen so that the appropriateness of the model can be assessed.

The characteristics of simulation objects will be defined in terms of, for example, capacity or speed of operation, and when the structure of the model has been confirmed a number of trials can be run and the performance of the system described statistically. Statistics of interest may be average waiting times, utilisation of work centres or resources, etc.

Simul8 Corporation have produced a number of ‘plug-ins’. These are auxiliary software packages which enhance the facilities if SIMUL8 in a number of specific areas. The instructions in this workbook make no reference to the use of plug-ins, and they are equally valid whether or not plug-ins are present.

Simul8 utilises Windows graphics rather having its own graphics programmed into the package. This has three advantages. First it simplified the writing of the Simul8 software. Second it enables the graphics to run efficiently in the Windows environment. Third it presents the user with a familiar graphics style.

The version used in compiling this booklet is Windows XP. If your computer is using a different version of Windows then there will be some small variations in the graphics (for example dialogue box colours may be a slightly different shade and the shapes of option buttons may be slightly different), but all functionality will be the same.
1.1.2 The Building Blocks

In a simulation model there are four main building blocks which are listed below.

1. Work Entry Point
   - This is where work items (be they machine parts, ships or virtual items like telephone inquiries) arrive in the system.
   - The pattern of arrival of work items can be controlled to follow a scheduled arrival pattern (deterministic behaviour) or a particular probability distribution (stochastic behaviour).
   - There can be more than one Work Entry Point as more than one type of raw material may be required, and they may enter at any stage of the process.

2. Queue
   - This is where work items are held while waiting to be processed. Queues may be storage areas in a manufacturing system, virtual queues in call centres, etc.
   - The simulation analyst can control the capacity of the queue, the shelf life of items in a queue, and the queue discipline.

3. Work Centre
   - This is where work is performed by a machine or server.
   - The length of time the work takes can be controlled to follow a particular probability distribution.
   - The output can be routed to other objects in a variety of ways.

4. Work Exit Point
   - This is where work leaves the system.
   - There can be more than one Work Exit Point. For example:
     - in a manufacturing process simulation, satisfactory products may be sent to a warehouse and defective items may be sent to a scrap bin,
     - in a call centre simulation there may be a ‘completed calls’ exit and also a ‘dissatisfied callers’ exit for callers who fail to reach an operator.

There are two other important elements in a simulation.

1. Work Items
   These are the objects that are generated at work entry points and are then processed by the simulated system.

2. Resources
   These are necessary when processes at simulated work stations compete for resources, such as when only one operator is available to set up processes on several machines.
1.1.3 Starting SIMUL8

Start up SIMUL8.
How you do this will depend on how the package has been installed on your system.

In the Simul8 2005 dialogue box which appears, click on Create a new blank simulation.

In Simul8 2005 the menu-bar and toolbar look like this. (There may be some variation in location of items on the toolbar, depending on how the layout was initialised on your system.) One of the buttons has been labelled below.

Run the mouse pointer over the toolbar to find out what each button means, and label the buttons in the space below.
1.1.4 Conventions used in these notes

- In the following instructions, the notation / File / Save as… will be used to refer to items selected from the menu bar (for example, meaning to click on File on the menu bar, then click on Save as… in the File menu).

- When referring to buttons on the toolbar, items in dialogue boxes, etc, key words will be highlighted.

- Key words will also be highlighted for other actions that you have to take, for example selecting options in a dialogue box.

- Lines beginning with a † (“do it”) symbol are computer instructions, requiring an action from you. You may find it useful to tick each “do it” box as you complete it. Anything else is an explanation, not requiring an action from you.
1.2 Building your own model

You will now start to build a model to simulate the operation of a factory that manufactures gears from raw mouldings.

In your initial simulation of a simple factory, as shown below,

(i) gear mouldings arrive in batches (Deliveries);
(ii) they enter a storage area while waiting (ie queuing) for processing (GrindQ);
(iii) the gear mouldings are ground into gears at three grinders working in parallel (Grind 1, Grind 2 and Grind 3);
(iv) the ground gears go directly for washing (Wash);
(v) the washed gears leave the factory (Dispatch).

Note that, because there is no storage area between grinders and washer, whenever the washer is in use, any other ground gear waiting for the washer must stay on the grinder until the washer is free.

You will start with a system in which arrivals and processing times are deterministic (fixed, with no uncertainty) so that the operation of the system is clear. You will specify the pattern of arrivals, the capacity of the storage area and the service time at each work centre.

You will then convert the system to have stochastic arrivals and processing times (variable, subject to some uncertainty).

Finally you will extend the factory so that the washed gears are polished and inspected before leaving the factory.

In later sections you will then extend this simple model to include more complex behaviour such as scrapping and reprocessing of faulty items, and prioritising work.
1.3 Gear manufacturing - deterministic simulation

1.3.1 Creating the model

Start by creating a model like this, with only one of each type of work centre:

Create the model layout working from left to right across the screen, then adjust the locations of icons as necessary.

- First create a **Work Entry Point** by clicking on the **Create Work Entry Point** tool then clicking somewhere near the top left-hand corner of the blank **Simulation Window**.

Having started with a work entry point, if you continue to add icons sequentially without interrupting (to correct errors for instance), you will find that simul8 automatically puts in routing arrows until you insert the work exit point.

If you do interrupt the sequential adding of icons, then you can add the routing arrows afterwards.

- Create a **Storage Area** (Queue) for the incoming work items using the **Create Storage Area** tool in the same way.
- Create a single **Work Centre** (Activity) for grinding using the **Create Work Centre** tool.
- Create a second single **Work Centre** for washing, again using the **Create Work Centre** tool.
- Create a **Work Exit Point** using the **Create Work Exit Point** tool.

You should save frequently while working.

- Use **/ File /Save as...** (ie click on **File** on the menu bar, then click on **Save as...**.
- Give the **Filename** as **Gear1a** and click on **OK**.
If you make a mistake you can edit the model. Even if you made no mistakes, practise editing your model as follows.

- If you create the wrong type of object
  - double click on the object
  - in the dialogue box that appears, click on the Erase button
  - in the Simulation Assistant dialogue box that appears, confirm the erase command by clicking on Yes
  - create the correct icon using the appropriate tool

- If you need to move an icon you can click and drag it to another location

If you make no mistakes and do not edit the model then all the routing arrows will be put in for you correctly. If you need to modify the routing arrows then there are two methods. Try each method even if you have made no mistakes.

- To remove an existing link or create a new one - Method 1
  - hold down the Shift key
  - click and drag from the source object to the destination object

- To remove an existing link or create a new one - Method 2
  - click on the Route Drawing Mode button
  - click and drag from the source to the destination object
  - click on the Route Drawing Mode button to switch it off

It is good practice to define a work item type so that the name is meaningful. In this case you will use the name Gear.

- Use / Objects / Work Item Type (ie click on Objects in the menu bar, then click on Work Item Type in the Objects menu)

- In the Work Item Type dialogue box change the name from Main Work Item Type to Gear

- Click on OK to close the dialogue box

Modify the work entry point graphics to display the title and the count of the cumulative number of simulated work items that have arrived.

- Double click on the Work Entry Point icon in the simulation window

- In the Work Entry Point Properties dialogue box change the name to Deliveries then confirm that the Input Work Item Type is Gear (but do NOT press the enter key yet)

- Click on the Graphics button

- In the Graphics: Work Enters Object dialogue box ensure the Count option is selected, then click on the Title button

- In the Simulation Object Title dialogue box select Show Title on Simulation Window, then click on OK in each dialogue box to go back to the Work Entry Point Properties dialogue box
Define arrivals as a batch of 15 gear mouldings arriving every 60 minutes.

- In the **Work Entry Point** dialogue box, click on the **Distribution** selector arrow and select **Fixed** (which you will find near the top of the list)
- Change the **Fixed Value** to **60** minutes between batches (but do NOT press the Enter key)
- By default Simul8 assumes that the units are minutes. You will look at this in more detail later.
- Click on the **Batching** button and in the **Batching** dialogue box ensure the distribution is set to **Fixed** and change the **Fixed Value** to **15** work items per batch
- Click on **OK** in each dialogue box to go back to the model

Define the characteristics of the storage area (queue or buffer) to have a capacity of 25 gear mouldings. This means that if there are more than ten raw mouldings in the storage area when a scheduled delivery of 15 raw mouldings is made then the number delivered is reduced so that the queue length does not exceed 25 (ie by rejecting one or more of the raw mouldings when they arrive).

- Double click on the **Storage Area** icon
- In the **Storage Bin Properties** dialogue box change the **Name** to **GrindQ**
- Change the **Capacity** to **25** (so that balking occurs when the queue reaches this size)
- Leave the **Shelf Life** as **Infinite** (so there is no reneging)
- Click on the **Graphics** button
- In the **Storage Bin Graphics** dialogue box, select **Static Image** from the **Display Style** options, confirm that the **Count** option is **ticked**, then click on the **Title** button
- In the **Simul8 Object Title** dialogue box select **Show Title on Simulation Window**, then **OK** back to the model

You will next create a single grinding work centre with the correct characteristics (taking 10 minutes to grind each gear), and then you will make two copies of it. As they all operate in the same way, this is more efficient than setting up the three work centres separately.
Define the characteristics of the first work centre.

- Double click on the **Work Centre 1** icon
- In the **Work Centre Properties** dialogue box change the **Name** to **Grind 1**
- In the **Distribution** options box click on the **New** button
- In the **New Distribution** dialogue box change the default name to **GrindDist**, select **Named Distribution**, and click on **Next>>**
- In the **Named distribution** dialogue box select the type of **Distribution** to be **Fixed** with a **Fixed Value** of **10** minutes
- The default graphics are suitable, so **OK** back to the model

The reason for creating a named distribution is that there will be two more grinding work centres, each with the same distribution. Later you will modify the distributions in all three work centres simultaneously by modifying the named distribution.

Create two other identical work centres.

- Hold down the **Ctrl** key, then **drag** the **Grind 1** icon to a new location and **release** to create an identical work centre, which will automatically be given the name **Grind 2**
- **Repeat** this to create the third identical grinding station with the name **Grind 3**

Set up the washing work centre.

- Rename **Work Centre 2** as **Wash**, give it a **Fixed** time of **2.75** minutes
- The default graphics are suitable, so **OK** back to the model

This is not defined as a named distribution because it is only used at one work centre.

Define the characteristics of the work exit point.

- Double click on the **Work Exit Point** icon
- In the **Work Complete Properties** dialogue box change the **Name** to **Dispatch**
- Click on the **Graphics** button
- In the **Graphics: Work Complete Object** dialogue box ensure the **Display Style** is **Image+Count**, then click on the **Title** button
- In the **Simul8 Object Title** dialogue box select **Show Title on Simulation Window**, then **OK** back to the model
Your model should now look something like the one shown above.

By default the simulation results collection period is just under 2400 minutes (40 hours, ie 8 hours per day, Monday to Friday). Simul8 allows the user to specify a warm-up period at the start of the simulation, during which results are ignored. This is set to zero by default, but it would be sensible to set it to just less than 60 minutes because there will be no arrivals during this initial period.

- Use / Clock / Clock Properties and in the Clock Properties dialogue box confirm the Simul8 default options:
  - in the Time Units options the units used are Minutes
  - in the Time Format options Time & Day and Clock Face are selected
  - in the Days options Days and Mon, Tues, Wed… are selected, and the Days per week is set to 5
  - in the Running Time options Start time each day (HH:MM) is set to 09:00 and Time in each day is set to 08:00
  - then click on OK

- Click on Warm Up Period, in the Warm Up Period dialogue box change the warm-up period to 59.99 (just less than 60 minutes so that the first arrival will be just after the end of the warm up period and will be included in the results collection period), then OK back to Clock Properties dialogue box

- In the Clock Properties click on Results Collection Period change the results collection period to exactly 2400, then OK back to the model

Run the simulation.

- Click on the Run tool and observe the animated simulation

- Adjust the Speed slider in order to watch the simulation at slow speed for the first few batches of arrivals

- Increase the Speed and notice the simulation clock going faster

- Set the Speed slider to maximum to suppress the animation and finish the simulation run quickly
When the simulation runs you should see the following.

(i) The number above the Deliveries icon shows how many work items have entered the system.

(ii) The number above the GrindQ icon shows how many work items are in the storage area (i.e., in the queue) for the grind work centres.

(iii) The numbers over Grind icons and the Wash icon show whether each work centre is occupied (1) or not (0).

(iv) The number over the Dispatch icon shows the number completed.

It is more helpful to show the queue graphically as well as numerically.

☐ Double click on the GrindQ icon and in the Storage Bin Properties dialogue box click on the Graphics button.

☐ In the Display Style options select Queue, then OK back to the Simulation Window.

☐ Click on the Run tool and adjust the Speed slider in order to watch the simulation at slow speed for the first few batches of arrivals.

You should now find it easier to observe the arrival behaviour.

Notice also that there is no buffer between Grind Work Centres and the Washer, so jobs will not move from Grind work centres until the Washer is ready for them.

☐ Use the Show/Hide Route Arrows tool to display the route arrows while the simulation is running.

Showing the route arrows during runtime is particularly helpful when verifying the structure of larger, more complex models.

☐ Increase the Speed and notice the simulation clock going faster, then set the Speed slider to maximum to suppress the animation and finish quickly.

You may have noticed that the two small black squares in the ‘display queue’ icon are the locations of the first two work items in the queue. So these markers define the direction and spacing of queue items. By default the direction is horizontal, but it may be helpful to change this if there is another icon close by.

☐ Ensure that the Route Arrows are displayed so that the queue icon is visible while running, like this.

☐ With the simulation stopped, but the Route Arrows displayed, carefully click once on one of the small black markers and drag to adjust its position within the icon.

☐ Experiment with the two markers to make the queue lie downwards to the left, with the queuing items reasonably close together, something like this.

☐ Save the model (still as Gear1a).

A careful layout can help to make a model easier to interpret and verify. There are no hard and fast rules but, for example, lining up the icons in rows, with route arrows horizontally left to right or diagonally downwards to the right where possible makes the models more ‘readable’.
1.3.2 Travel times

SIMUL8 is designed to mimic the layout of a factory or other organisation, and it assumes that the travel time of work items between simulation objects such as work centres and queues may depend on the distance. The following default assumptions are used:

(i) the travel time from a Work Entry Point to a Queue is zero,
(ii) the travel time from a Queue to a Work Centre is zero,
(iii) the travel time from a Work Centre to another Work Centre is zero,
(iv) the travel time from a Work Centre to a Queue is non-zero and related to the on-screen distance,
(v) the travel time from a Work Centre to a Work Exit Point is non-zero and related to the on-screen distance.

For many simulations it is better not to have non-zero travel times by default. You should generally set up your SIMUL8 models with the travel times set to zero, and put them in explicitly when needed.

Initially observe the times of events with non-zero travel times in the model. You will use the Step tool which causes the simulation clock to jump from one event time to the next. You will notice that when a number of events occur simultaneously they are shown on screen sequentially without the clock time moving on.

- To observe the times of events more easily use / Clock / Clock Properties
  - set the Time Format to Digital
  - set the display option to HH:MM:SS
  - click on OK

- Drag the simulation clock from the top right corner of the screen and locate it close to the model to make it easier to see the times when events occur while the model is running slowly

- Click on the Reset Clock to Start tool
  Simul8 automatically resets the model if you click on the Run tool after a complete run. However, when you want to use the Step tool you will need to Reset the model yourself.

- Set the speed to slow and click on the Step tool successively until one complete batch has gone through the system and the next has arrived

You should notice that although all distributions are set to Fixed, in multiples of a quarter of a minute (time between batches 60 minutes, grind time 10 minutes and wash time 2.75 minutes), there will be event times that do not occur exactly on the minute or multiples of 15 seconds.
For instance the time for work items to travel from Grind 1 to Wash, or from Wash to Dispatch depends on how far apart you placed the icons on the screen. If you had different distances, then the times of events would be slightly different, reflecting the new simulated travel times.

Now set the travel times to be automatically =zero, and ‘step through’ the model again.

- Use / Tools / Preferences… and select the Distance page by clicking on the nametab
- In the Travel Times options click on the =Zero button
- In the Simulation Assistant dialogue box respond Yes to the question Are you sure you want to set all travel times to zero?
- Then OK back to the model
- Click on the Reset Clock to Start tool
- Click on the Step tool successively until one complete batch has gone through the system and the next has arrived

You should now observe that all event times are exactly on the minute or multiples of 15 seconds. With zero travel time you should also observe that the last work item of the batch arrives at Dispatch at 10:58:15, ie just 1 minute 45 seconds before the next batch arrives.

When a model runs with zero travel time between objects, the individual work items are still shown to be moving with finite speed on the screen animation to help to user check the model, but the simulation clock is stopped while this is happening.

- Run the model
  - slowly initially, to observe that the screen animation does not appear to have changed from when travel time was related to on-screen distance, but the simulation clock is stopped when travel takes place
  - then faster to observe the overall pattern of movement of the work items
  - and finally at maximum speed to suppress the graphics and finish quickly

- Reset and Save the model (still as Gear1a)
1.3.3 Results from the deterministic model

1.3.3.1 Work exit point results

The simplest set of results comes from the Dispatch work exit point.

- With the model that you saved as Gear1a, if the Reset Clock to Start tool has been used then Run the model with a Warm Up Period of 59.99 and a Results Collection Period of 2400.
- Double click on the Dispatch icon.
- In the Work Complete Properties dialogue box click on the Results button.

You should see the Work Complete Results dialogue box, as shown below.

The Work Completed result gives the total number of work items through the system (40 hourly batches x 15 per batch = 600).

In the Time in the system results the maximum is 58.25 minutes so each hourly batch clears the system before the next arrives.

- Click on the Histogram icon.

The Time in Simulation: Dispatch graph presents a frequency distribution of time in system.

- Stretch the horizontal axis so all the interval labels are displayed.

The interval labels are displayed to the nearest integer, and this may seem to imply that the intervals are not of equal width. However there are always 10 equal intervals, over a range which ‘captures’ the minimum and maximum values.

The graph looks a little odd because every frequency is either 6.67% or 13.33%. The reason is that, of the 15 Work Items in each identical hourly batch, either one or two will fall in each interval.

In any simulation, this frequency distribution can be used to give a quick visual overview of an important aspect of system performance.
The graph should appear to roughly agree with the summary numerical statistics, and in this example you should see that
- the graph looks reasonable for the min and max (12.75 minutes for the first one in each hourly batch and 58.25 minutes for the last one),
- the average (35.5 minutes) is somewhere around the middle of the graph.

Confirm that the time in system within limit results appear to agree with the graph.

- In the **Work Complete Results** dialogue box click on the **Time limit** value. The cursor will change to a large black arrow and a Simulation Assistant window will pop up advising you that you can add this value to a results summary by right-clicking the box. You will learn about using right-click for results collection later.
- Change the **Time Limit** to 20 minutes, then 40 minutes, note the **Percentage within limit** result for each, and compare with the graph. You should find that 20% of work items pass through the system within 20 minutes, and 60% within 40 minutes. You should also see that the graph appears to agree with these results.
- Change the **Time Limit** to 60 minutes. You should see that 100% pass through the system in less than an hour.
- Close the graph and **OK** back to the model.

### 1.3.3.2 Queuing time results

Look at some results for the GrindQ storage area. With the current Graphics options the GrindQ icon is displayed when the simulation is running. However, when the simulation is not running the icon is only displayed if the route arrows are displayed.

- Click on the **Show/Hide Route Arrows** button to help locate the **GrindQ** icon.
- Double click on **GrindQ**.
- In the **Storage Bin Properties** dialogue box click on **Results**.

The Storage Bin Results window, shown here, gives results related to:
- the **number** of work items in the queue (which varies over time),
- the **time** that work items spend in the queue (which varies between work items).
Start by looking at the Queuing Time results. These results are summarised both graphically and numerically.

First look at the graphical display, then at the numerical summary.

- Click on the **Histogram** button in the **Storage Bin Results** window. This shows the frequency distribution of queuing times. On the horizontal axis, the range from zero to the maximum waiting time is divided into 10 equal intervals (with the interval boundaries displayed to the nearest whole number).
- Stretch the horizontal axis so all the interval labels are displayed.

Again it may appear that the intervals are not of equal width, but this is because the interval labels are displayed to the nearest integer.

The graph again looks a little odd. Every frequency is either 0%, 6.67%, 13.33% or 20% because, of the 15 work items in each identical hourly batch, each interval will ‘capture’ either none, one, two or three of them.

The graph should appear to be roughly in agreement with the summary numerical statistics for All work items. You should see that the graph looks about right for the min and max (0 and 45.5), and the average (22.2).

The summary statistics are also given for the Non-Zeros, ie ignoring the work items that do not have to queue (the first three in each batch). The number of non-zero queuing times is reported as 480, so there were 120 work items (the first 3 in each of the 40 batches) that did not queue.

The queuing time results include the percentage of work items queuing for less than the specified limit.

- In **Queuing Time within limit** find the **Percentage within limit** when the **Time limit** is 20, 40 and 60 minutes, and check that these results appear to agree with the graph.
- Close the graph.
1.3.3.3 Queue length results

The **Number of work items in this storage** results are summarised both graphically and numerically. First look at the graphical display.

- In the **Storage Bin Results Window** click on the **Time Graph** button, and stretch the **Contents: GrindQ** graphic window horizontally.

The changing of the queue length over 40 cycles from the end of the warm up period until the end of the results collection period is shown below.

In each cycle there is instantaneous replenishment of the stock (with 3 going directly into the Grind work centres and only 12 remaining in the queue) followed by a decline to zero, then a short period with no queue before the next replenishment.

The average number of work items in the queue (ie average queue length) over the results collection period is displayed as a horizontal dotted line and is shown on the vertical axis to 1 decimal place.

Now look at the graphical display.

- In the **Storage Bin Results** window, look at the **Number of work items in this storage** results.

The Minimum is zero just before each batch arrival.

The Maximum is 15.00 when each batch arrives, but only instantaneously because three immediately move into the grind Work Centres and a maximum of only 12 appears on the time chart.

The Average is 6.00 which agrees with the average displayed on the chart.

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The numerical Number of work items in this storage results and the Time Graph results use the same data, and there are two options controlling the collection of the relevant data during the simulation run. The default option is Sync(hronise) with other results, and under this option the queue length is sampled over time.

The sampling times do not generally coincide with critical events in GrindQ (such as when the queue length changes). So the graph will only approximate to the actual simulation, and the numerical results will only be approximately correct. It is feasible to collect exact data from the simulation using the other Graph option, namely Plot every change. So why is the approximate approach used as the default option?

The answer is that real applications of Simul8 do not use simple, small, deterministic models. In realistic applications with bigger, more complex models collecting results from longer run-times with stochastic behaviour, the errors in the approximate method tend to cancel out. The approximate method then enables data to be collected faster with no significant loss of information in the graphical results.

Change the graph option in order to collect exact simulation results.

- Close the Graph and in the Storage Bin Results dialogue box change the Graph option to Plot every change.
- OK back to the model and Run the model again to collect the exact data.
- Open the Storage Bin Properties dialogue box and click on Results.

The Average Number of work items in this storage is now based on exact data.

- Open the Time Graph

The time graph is now based on complete data, and the correct average is displayed (but rounded to one decimal place).

- Close the Graph and OK back to the model.
1.3.3.4 Work centre results

Look at the results for one of the grinders.

- Double click on the **Grind 1** icon, then on the **Results** button

In the Work Centre Results dialogue box, the statistics for the Number of work items in the grinder are listed first.

The number of work items on the machine is always either zero or one, so the Average (0.83) is the proportion of time when the grinder is occupied.

- Click on the **Graph** button
- Stretch the **Contents: Grind1** graphic window horizontally to see the pattern of occupancy over time more clearly

There should be 40 one-hour periods, in each of which there is a short idle period just before the next hourly batch arrives.

The average occupancy level is indicated by a horizontal dotted line and is displayed on the vertical axis (0.8 to one decimal place).

- Close the graphic window
- Inspect the **Percentage of Time** results

The percentage of awaiting work should be the same as the average number of work items in the work centre, but is displayed to a higher degree of precision.

- Click on the **pie chart** button

This should show the proportions of time working and waiting for work. It is not a very informative display.

- Close the pie chart and OK back to the model

When you save a model as a file in SIMUL8, you also save all the results if there are any. This can make your files very large, especially if you have a big complex model and/or you are collecting a lot of results from long simulation runs. So it is good to get into the habit of resetting before saving.

- Click on the **Reset Clock to Start** button
- Save the model (still as **Gear1a**)

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1.4 Gear manufacturing - stochastic simulation

In this section you will convert to a stochastic model

- by making inter-arrival times exponentially distributed,
- by making grinding times exponentially distributed,
- by making washing times Normally distributed.

The arrivals were previously in batches of 15 every hour, and an average arrival rate of 15 per hour is equivalent to an average time between arrivals of 4 minutes. Now make the gear mouldings arrive singly and at random, but with this same average arrival rate.

- With the model you saved as Gear1a, double click on the Deliveries icon
- In the Work Entry Point Properties dialogue box change the Distribution to Exponential with Average equal to 4
  (Times between randomly occurring events are Exponentially distributed)
- Change the Batching to Fixed = 1
- OK back to the model

Make the grinding times stochastic by changing the grinding distribution, which is used at all three grinding stations, to an exponential distribution with mean 10.

- Use / Objects / Distributions and select GrindDist, then click on Properties
- In the Named Distribution dialogue box, set the Distribution to Exponential with Average equal to 10
- OK back to the model

This demonstrates one of the advantages of having named distributions. The same distribution is used by the three grinders and you do not have to edit each of the work centres separately to modify the distributions.

Make the washing time Normally distributed with mean 2.75 and standard deviation 0.5.

- Double click on the Wash icon
- In the Work Centre Properties dialogue box change the washing time Distribution to Normal
- Set the mean = 2.75 and the standard deviation = 0.5
- OK back to the model
Run the model, showing the time graph of queue length. The toolbar has a shortcut to queue length chart which you can practise now.

- Click on the **Reset Clock to Start** tool
- Click once on the **GrindQ** icon to select it (using the **Show/Hide Route Arrows** tool if you find it helps to make it clear exactly where the GrindQ icon is)
- On the toolbar, click on the **Make Time Graph of selected object** tool
- Stretch the empty **graphic window** horizontally
- **Run** the simulation slowly at first to observe the detailed behaviour, then faster to get an overview of the changing queue length, and finishing at maximum speed to end the simulation quickly without the graphics

You should see the time graph of queue length building up progressively as more and more results are collected. This facility can be useful when building a simulation model, as a quick check to see if the model is behaving roughly as expected.

You may get a **HINT: Work items blocked from entering model** message. This can happen if a series of mainly long grinding times coincides with short inter-arrival times, causing the queue length to reach 25 (the maximum allowable queue length).

If so, the Deliveries work entry point rejects any further simulated arrivals until the queue length is below 25 again. This is an example of **balking** in a queuing system.

- If you get this message select the **Don't give this hint again for this work entry point** option, then click on **OK** to complete the simulation

Run again with different random numbers.

- Use **/ Clock / Change Random Numbers and Run**, running the simulation fast to get the results for a different (but equally likely) scenario, and notice that the queue length chart has been revised

There is an alternative way of running the model with a different set of random numbers.

- Click on the **Run selector arrow**
- In the drop-down menu that appears select **Run with new random numbers**
- **Repeat** with other random numbers and notice that in the results chart the queue length never exceeds 25
- **Close** the **Time Graph**, click on the **Reset Clock to Start** button and **Save** the model as **Gear1b**
1.5 Adding more operations - polishing and inspecting

You will now extend the factory so that the washed gears are polished and inspected before leaving the factory.

(i) The washed gears go to a storage area, assumed to have limited capacity (maximum 20 work items), before being polished.

(ii) This storage area serves two polishers working in parallel.

(iii) The polished gears go to a storage area, assumed to have limited capacity (maximum 10 work items), before being inspected.

(iv) This storage area serves a single inspection station.

(v) The inspected gears then go for dispatch.

Your model will look similar to this:

Create a single polishing work centre preceded by a storage area. (Don’t put in links yet.)

- Ensure the routing arrows are displayed by clicking on the **Show/Hide Route Arrows** button if necessary
- **Click and Drag** the Dispatch icon away from the Wash icon to make room for an additional icon
- **Remove** the link from Wash to Dispatch by holding down the Shift key, clicking on the source object then **dragging** onto the destination object
- **Use the Create Storage Area** button to create a new buffer and position it after the Wash icon
  - change its **name** to PolishQ
  - change its **capacity** to 20
  - use the **Graphics** options to display Queue, Count and Title
- **Use the Create Work Centre** button to create a new work centre
  - **locate** it after the PolishQ icon
  - change its **name** to Polish 1
  - change its **Distribution** to Normal with **Average (mean)** = 6 and **Std Dev** (standard deviation) = 1
- use the **Graphics** options to display **Image**, **Title** and **Count**
Create an inspection work centre preceded by a storage area.

- Create a **Storage Area**, located after the **Polish 1** icon, called **InspectQ** with **Capacity = 10**, displaying the **Queue, Count** and **Title**
- Create a single **Work Centre**, located after the **InspectQ** icon, called **Inspect**, having an **Exponential** distribution with **mean = 2.5**
- displaying **Image, Title** and **Count**

Put in the necessary links and then create a duplicate of the single polishing work centre.

- Create **links** from **Wash** to **PolishQ**
- from **PolishQ** to **Polish 1**
- from **Polish 1** to **InspectQ**
- from **InspectQ** to **Inspect**
- from **Inspect** to **Dispatch**
- Click on the **Polish 1** work centre, hold down the **Control** key and **drag** to one side to create **Polish 2**
- **Adjust** the of the new **icons**, and the spacing and direction of **queues** to improve the presentation of the model

Run the model.

- **Run** at slow speed initially to observe the model working, then finish the simulation run at maximum speed
- **Inspect the Results**, especially the **graphs** of queue lengths over time
- **Run the model with new random numbers** a few times at full speed, and each time look at the **graphs** of queue lengths over time

You should see that there are generally longer queues in GrindQ than in either PolishQ or InspectQ.

- **Close** all results windows, click on **Reset Clock to Start** and **Save** the model (still as **Gear1b**)

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2. CONTROLLING THE SIMULATION EXPERIMENT

In this section you will learn how to control the simulation so that appropriate results are collected, and how to interpret the results.

It is therefore about the technical aspects of running simulations, rather than about the logic of building simulation models.

Your current model (Gear1) has stochastic arrivals and processing times, and buffer capacities as follows:

<table>
<thead>
<tr>
<th></th>
<th>Arrivals</th>
<th>Queue for grinders</th>
<th>Grinders (3)</th>
<th>No buffer for washer</th>
<th>Washer (1)</th>
<th>Queue for polishers</th>
<th>Polishers (2)</th>
<th>Queue for inspection</th>
<th>Inspection (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exponential inter-arrival times, mean 4 minutes</td>
<td>Capacity 25 gears</td>
<td>Exponential service times, mean = 10 minutes</td>
<td></td>
<td>Normal service times, mean = 2.75 minutes, mean service capacity ≈ 22/hour, sd = 0.5 minutes</td>
<td>Capacity 20 gears</td>
<td>Normal service times, mean = 6 minutes, mean combined service capacity 2x10 = 20/hour, sd = 1 minute</td>
<td>Capacity 10 gears</td>
<td>Exponential service times, mean = 2.5 minutes, mean service capacity = 24/hour</td>
</tr>
</tbody>
</table>

In the long run, the service capacity throughout the system exceeds the average arrival rate. However the stochastic behaviour can never-the-less cause queues: if service times are longer than average and/or work items enter the corresponding queue faster than average, then there is a likelihood of a temporary bottleneck. Stochastic simulation assesses the impact of the uncertainty on the system behaviour.
2.1 The warm-up period

With no warm up period, look at the effect of different random number sequences on the time plot of the number of work items in the GrindQ storage area.

- Open your final Gear1b model and Save as Gear2
- Use / Clock / Warm Up Period to set this to zero
- Use / Clock / Results Collection Period to set this to 2400
- Select GrindQ, click on the Make Time Graph of selected objects button, and stretch the graphic window horizontally
- Use / Clock / Run to run the model, initially at visible speed then at maximum speed to suppress the animation
- Use / Clock / Change Random Nos and Run to get another set of results and again inspect the GrindQ queue length time plot
- Repeat for a few more (equally likely) scenarios with new sets of random numbers

You should observe that:

- (i) each new set of random numbers produces a different time plot;
- (ii) in general, because the simulation starts off with nothing in the system, the average length queue in the initial part of the time plot will tend to be less than the average in the later part of the time plot;
- (iii) so the average queue length and average queuing time in the initial transient period are less than the corresponding long-run averages.

A ‘transient period’ or ‘warm up period’ at the start of a simulation run can be ignored so as not to bias the results, and allow the system to approach a ‘steady state’ (when the probability of a work item having to queue has reached a steady level) before collecting results.

Set up the model to ignore the first 480 minutes (equivalent to one 8-hour shift), in order to allow work items to become spread throughout the system, and collect results for the subsequent 2400 minutes (equivalent to five 8-hour shifts).

Modify the model to include a warm up period.

- Use / Clock / Warm Up Period to the Number of Time Units to 480, then click on the Results Collection Period button and ensure that the Number of Time Units is 2400
- Click on the Bleep on Completion option and OK your selections
- Run the model
- If you find that the Bleep on Completion annoys you, then remove it
- Inspect the GrindQ time graph of queue length
Do a few more simulation runs at maximum speed.

- Use / Clock / Change Random Nos and Run, for each simulation run and each time look at
  - the GrindQ queue length time plot
  - the total number entering at Deliveries (displayed over the icon)
  - the total number leaving at Dispatch (displayed over the icon)

The graph will not necessarily show zero queue length at the start of the results collection period because the warm up period allows work items to be distributed throughout the system.

The number distributed throughout the system will vary over time because the number leaving will not, in general, match the number entering during any given simulated time period. In particular the number leaving (at Dispatch) during the results collection period will not necessarily be the same as the number entering (at Deliveries) during the same period.

- Close the Graph
- Reset and Save your model (still as Gear2)

2.2 Variation between runs

In simulation studies you will frequently be interested in how much variation there is from day to day, week to week, or month to month. The result collection period is commonly chosen to reflect an appropriate operating period.

To investigate the variation from period to period requires a number of replicates (repeated runs) of the same simulation model for the same period but with different streams of random numbers.

First you will perform 5 replicates or runs of the simulation under manual control, using Random Stream Set 1, Random Stream Set 2, and so on up to Random Stream Set 5.

Then you will see how to automate the process with the same random number sets (to get the same results).
Obtain the number of work items completed result for the first replicate and record it.

- Confirm that the **Warm Up Period** and **Result Collection Period** are **480** and **2400** minutes, respectively.
- In order to specify the random number stream for the first replicate use **/ Trials / Random Sampling**, and in the **Random Sampling Parameters** dialogue box set the **Random Stream Set Number** to **1** then click on **OK**.
- **Run** the simulation at maximum speed with no animation, look at the **Results** for the **Dispatch** point and record **Work Completed** for the **first** replicate in **Table 2.2a**.

This result is also shown above the Dispatch icon after running the simulation.

<table>
<thead>
<tr>
<th>Replicate</th>
<th>Number of work items completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td></td>
</tr>
<tr>
<td>standard deviation</td>
<td></td>
</tr>
</tbody>
</table>

Perform a second replicate, again using the Trials menu to specify the random number stream.

- Change the random number stream using **/ Trials / Random Sampling**, and in the **Random Sampling Parameters** dialogue box change the **Random Stream Set Number** to **2** then click on **OK**.
- **Run** the simulation at maximum speed with no animation, and in **Table 2.2a** record the **Number of work items completed** (the value over the **Dispatch** icon) for the **second** replicate.

Perform the third replicate, this time using the Clock menu to specify the random number stream.

- Use the **/ Clock / Change Random Nos and Run** and in **Table 2.2a** record the **Number of work items competed** for this **third** replicate.
- To check the random number stream that you have just used for the third replicate, use **/ Trials / Random Sampling**, and in the **Random Sampling Parameters** dialogue box confirm that the **Random Stream Set Number** was automatically increased from **2** to **3**, then click on **OK**.
Perform the fourth and fifth replicates using the Run tool options.

- Click on the Run selector arrow
- In the drop-down menu select Run with new random numbers
- Record the Number of work items completed for the fourth replicate in Table 2.2a
- Use / Trials / Random Sampling to confirm that the random number stream that you have just used for the fourth replicate was automatically increased from 3 to 4
- Perform the fifth replicate with a new random number stream and record the result in Table 2.2a
- Reset and Save your model (still as Gear2)

Any of these three methods can be used to change the Random Number Stream set in sequence from 1 to 2, 3, 4 and 5. The / Trials / Random Sampling facility gives most control and is particularly useful if you may want to run other simulations (with the system modified) using the same random numbers in order compare results.

Now look at the expected week-to-week variability in the simulated number of completed work items (each replicate simulating one week’s operation).

- For the five results in Table 2.2a calculate the mean and standard deviation (use a calculator or spreadsheet)
- Copy the mean and standard deviation into Table 2.2b below

The standard deviation (SD) is a measure of the variability in daily throughput, and approximately 95% of periods have a throughput in the range mean ± 2 SD. You are only able to estimate this range, rather than calculate it exactly, because your mean and standard deviation are only estimates of the true, long-run mean and standard deviation, based on a small sample of simulation runs.

Your estimate of the range within which 95% of daily throughputs are expected to lie is referred to as the 95% Predictive Interval for daily throughput. Calculate this estimated range and record it in Table 2.2b below (giving values to the nearest unit).

<table>
<thead>
<tr>
<th>Table 2.2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean = .......... sd = .............</td>
</tr>
<tr>
<td>so we estimate that 95% of working days will have a throughput between .......... and ............</td>
</tr>
</tbody>
</table>

If you were to use more replicates you would get better estimates for the mean and standard deviation, so you would get a more reliable estimate for the range within which the throughput will lie on 95% of working days.
2.3 Obtaining confidence limits

In the previous section you have investigated the week-to-week variability in actual throughput. Now you are going to obtain a confidence interval for the long-run average weekly throughput.

First you need to estimate the standard error of the mean. The formula is

\[ \text{standard error} = \frac{s}{\sqrt{n}} \]

where \( s \) is the standard deviation of the simulated weekly throughput values (the sample standard deviation) and \( n \) is the number of replicates (sample size).

If the sample size is sufficiently large then the approximate 95% confidence interval for your estimate of the (long-run) mean weekly throughput is obtained from the formula...

\[ (\text{observed mean}) \pm 2 \times (\text{standard error}) = \text{mean} \pm 2s/\sqrt{n} \]

However if the number of replicates (sample size) is small then the uncertainty in the estimate of the long-run mean value tends to be under-estimated by this formula and the standard error has to be multiplied by a larger number than 2.

For small sample size use the formula...

\[ (\text{observed mean}) \pm t \times (\text{standard error}) = \text{mean} \pm t s/\sqrt{n} \]

The statistic \( t \) in the formula above depends on the sample size, and the approximate values are shown in Table 2.3a below.

<table>
<thead>
<tr>
<th>sample size n</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9,10</th>
<th>11...13</th>
<th>14...27</th>
<th>28...</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t )</td>
<td>4.3</td>
<td>3.1</td>
<td>2.8</td>
<td>2.6</td>
<td>2.5</td>
<td>2.4</td>
<td>2.3</td>
<td>2.2</td>
<td>2.1</td>
<td>2.0</td>
</tr>
</tbody>
</table>

When the sample size (number of replicates) is small you should multiply the standard error by the \( t \)-value to derive the confidence limits.
For example...

if you run 5 replicates of 1 working week each and obtain 5 simulated throughput values with, say, a mean throughput of 590 work items and standard deviation 24,…

…then the standard error is 24 / \sqrt{5} \approx 10.7 …

…and the required t-value is approximately 2.8 …

…so the 95% confidence interval is 590 \pm 2.8 \times 10.7 \approx 590 \pm 30

In other words you are 95% confident that (if the assumptions of your model are correct) the long-run average weekly throughput will lie between 560 and 620 work items per week.

The above statement is about the estimated long run average, based on the sample of 5 results. Try to avoid confusing that with the estimate, based on the same sample of 5 results, that 95% of weeks will have a throughput of between 542 and 639 work items (ie mean \pm 2s = 542 \pm 2 \times 24).

Use the results from your 5 simulation runs, which you recorded in Table 2.2a, to calculate the approximate 95% confidence interval for the long-run mean number completed (weekly throughput) in Table 2.3b below.

<table>
<thead>
<tr>
<th>Table 2.3b</th>
<th>mean = ............</th>
<th>sd = ............</th>
<th>n = ............</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>so the estimated standard error is SE = ............</td>
<td>the t- value is t = ............</td>
<td>and the value of t \times s / \sqrt{n} is = ............</td>
</tr>
<tr>
<td></td>
<td>so the approx 95% confidence interval for the long-run mean weekly throughput is</td>
<td>between ............ and ............ (to the nearest unit)</td>
<td></td>
</tr>
</tbody>
</table>
2.4 Conducting a trial (multiple simulation runs) automatically

SIMUL8 uses the term Trial for running multiple replicates of a simulation. This can be automated using the Trials menu.

First set up the Result Summary to collect the results for the Average Time in the System, and the Dispatch Work Completed (the total simulated weekly throughput).

☐ With the model Gear2, confirm that the Warm-Up Period is 480 and the Results Collection Period is 2400 and run the model.

☐ Use / Results / Results Summary

You should see that the Average Time in System is the only result that is included by default.

☐ In the Simul8 Results Summary window click on the Detail button, and in the Objects window select Dispatch, then click on the Results button.

☐ Move the cursor so that it points on the Work Complete Results window at the Work Completed result (point at the actual value).

The pointer should change to a large black arrow with a white letter R.

☐ Right-click to add this result to the Result Summary, then OK back to the Results Summary window.

You should see that this result has been added to the results summary.

Note that this is a toggle so that a second right-click would remove the result from the summary.

☐ To practise this, click on the Detail button, in the Objects window select Dispatch, click on the Results button, then right-click on the Work Completed value.

☐ OK back to the Results Summary window to confirm that this result has been deleted.

☐ Add the Dispatch Work Completed value to the Results Summary again, then OK back to the model.

Include the Average Queuing Time in GrindQ in the results collection. This can be done via the GrindQ icon instead of via the Results menu.

☐ Double click on the GrindQ icon, and in the Storage Bin Properties window click on the Results button.

☐ In the Storage Bin Results window right-click on the Queuing Time: Average (for All work items) value to add this to the results summary.

☐ OK back to the model.

☐ Use / Results / Results Summary to confirm check that these results have been added.
Run a trial of 5 replicates automatically.

- Use / Trials / Conduct Trial
- In the Conduct Trial dialogue box
  - ensure that the Number of runs in this trial is 5
  - ensure that the Base Random Number Set is set to 1
    (as in the first of your manual replicates in Section 2.2)
  - click on OK and Run the Trial

The Result Summary appears automatically at the end of the trial.

- In Table 2.4a record the Average and the Confidence Interval for the Number Completed

This should give the same answer as your calculation of the confidence interval for the long-run average daily throughput. (But if you did not follow the instructions about the random number streams precisely then you will get a different estimate.)

- In Table 2.4a record the estimated long-run averages for the Time in System and the Average Time in GrindQ, and also the corresponding confidence intervals.

<table>
<thead>
<tr>
<th>Table 2.4a</th>
<th>Estimated long-run average using 5 replicates</th>
<th>95% Confidence Interval using 5 replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in System (minutes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number Completed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time in GrindQ (minutes)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Increase the precision with more replicates.

- Change the Number of runs in trial to 20 and repeat the Trial
- In Table 2.4b record the average and the 95% confidence interval for each parameter

You should observe an improvement in precision (reduction in confidence interval) when the number of replicates is increased.

<table>
<thead>
<tr>
<th>Table 2.4b</th>
<th>Estimated long-run average using 20 replicates</th>
<th>95% Confidence Interval using 20 replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time in System (minutes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number Completed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time in GrindQ (minutes)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.5 Variation between work items

The variation between individual work items (in terms of throughput times, times spent in queues, etc) can only be found in SIMUL8 from a single replicate (a single run of the simulation). This variation can be found by clicking on the appropriate icon after each single run of the simulation and inspecting the standard deviation results (as a measure of variability).

Look at the Time in the System results for single replicate.

- Run the model Gear2
- Double click on the Dispatch icon, then click on the Results button
- Record the Average and Standard deviation for the last run in Table 2.5a below (as the results of the replicate number 1 in that table)

The standard deviation shows how much variation there was in the throughput times of these work items.

<table>
<thead>
<tr>
<th>Table 2.5a</th>
<th>Replicate</th>
<th>Ave time in system</th>
<th>St dev time in system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results collection period</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compare with the frequency distribution of time in the system.

- In the Work Complete Results window click on the histogram button and inspect the histogram

You should find that the average and standard deviation that you recorded in Table 2.5a (for the time spent in the system by all the simulated work items in the last replicate of your trial) look roughly correct when inspecting the frequency distribution on the chart.

- Close the chart and OK back to the model

Now collect results for more replicates of the simulation.

- Click on the Run selector arrow, use Run with new random numbers, check the Average and Standard deviation in the Dispatch Results, and record in Table 2.5a above (as the results of the replicate number 2)
- Repeat for two more replicates
From each replicate you have obtained a sample standard deviation (ie each time using one sample out of the theoretically infinite number of scenarios that might have been simulated).

Different replicates give different estimates of the standard deviation, as a measure of the variability between individual work items.

If you want a better estimate from each replicate then you will need to take a larger sample. In other words you will need a longer results collection period.

The results in Table 2.5a are for replicates with a results collection period of 2400 minutes (one simulated working week). Changing the results collection period to 120 000 minutes (fifty simulated working weeks) will give a better estimate of the underlying variability in individual throughput times.

Try this now.

☐ Use / Clock / Results Collection Period to change this from 2400 to 120 000
☐ Collect four sets of results, each from a single replicate, and record these in Table 2.5b below
☐ Reset and Save (still as Gear2)

<table>
<thead>
<tr>
<th>Table 2.5b</th>
<th>Results collection period = 120 000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replicate</td>
<td>Ave time in system</td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

You should notice with larger samples of throughput times (from the longer results collection period of 120 000 minutes each time) that both the averages and the standard deviations are now more consistent (because each of these is now a better estimate, obtained from a larger sample of results).
2.6 Using Excel to analyse results

When you conduct a trial, Simul8 does not allow you to automatically access the trial results from all the individual replicates or runs of the simulation, except for the last one. However, the results from all replicates in a Simul8 trial can be accessed if they are copied to Excel.

Run a trial of 5 replicates of the simulation and copy the results to Excel.

- Use /Clock /Clock Properties to set the Warm Up Period to 480 and set the Results Collection Period to 2400, then OK back to the model.
- Use /Trial /Conduct Trial to set the Number of Runs in Trial to 5 and the Base Random Number Set to 1, then click on OK and Run the Trial.

The Results Summary should contain the following three results:
- Average Time in the System
- Dispatch Number Completed
- GrindQ Average Queuing Time

- If you do not have precisely these three results in the correct order, you should delete them, put them back in again in the correct order, then re-run the trial of 5 replicates before continuing.

- In the Results Summary window click on the Copy the Results to Clipboard button.

- Open up Excel, and on the first worksheet sheet select cell C3, then use /Edit /Paste.

Your results from all replicates of the trial are now in Excel.

The five individual Number Completed results should be the same as you recorded in Table 2.2a (if you followed the instructions precisely and used the correct random number streams throughout).

In Excel your results can be analysed or presented graphically. To illustrate possible analysis of results, confirm the Average results.

- For all non-integer values, reduce the number of decimal places to 1 to make the results more readable.
- Adjust column widths to make labels more readable.

In columns J, K and L you should have the same summary results that you recorded in Table 2.4a (based on the 5 replicates for which the results are now recorded in columns E to I).

- To confirm the three averages shown in column K, in cell M4 enter the formula =AVERAGE(E4:I4) and format to display 1 decimal place, then copy the formula down into M5 and M6.

- Confirm that your calculated averages agree with the average values in cells K4:K6, then Clear the contents of cells M4:M6.

- Save the Excel workbook.
Pasting the results into Excel is also useful for analysing the results of successive trials under different conditions. You can illustrate this by running trials with different average washing times.

- With the spreadsheet still open, in B2 enter the title *Ave wash time*, in B3 enter the value 2.75, and copy this value down as far as B6
- In B7 enter the formula =B3+0.25 and Format to display 2 decimal places, then copy down as far as B22
- Return to Simul8, then close the Results window, double click on the Wash icon and change the Average time to 3.00
- Run another Trial with the same base random number stream and the same number of replicates by clicking on the Make multiple runs... button on the main toolbar (it can also be found in the Simul8 Results Summary window)
- In the Simul8 Result Summary window click on Copy the Results to Clipboard
- Go into your Excel file, select cell C7 and use / Edit / Paste
- Repeat with the Average wash time set to 3.25, 3.50, and 3.75, pasting each successive set of results below the previous results

Your results from all five trials are now in Excel, ready for further analysis or graphical presentation. For example (as an optional exercise) you could illustrate graphically how the average time in the Wash Work Centre affects the queuing time in GrindQ.

- Select columns C:I and use / Edit / Delete
- To remove all except the queuing time results, select rows 3:5, then hold down the Control key and also select rows 7:9, 11:13, 15:17, 19:21, and then use / Edit / Delete
- In C2:E2 enter the titles Lower 95%, Ave Time in GrindQ and Upper 95%

You should be left with the following summary data (if you followed the instructions precisely and used the correct random number stream).

<table>
<thead>
<tr>
<th>Ave Wash Time</th>
<th>Lower 95%</th>
<th>Ave time in GrindQ</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.75</td>
<td>15.9</td>
<td>39.1</td>
<td>62.4</td>
</tr>
<tr>
<td>3.00</td>
<td>24.8</td>
<td>53.1</td>
<td>81.4</td>
</tr>
<tr>
<td>3.25</td>
<td>39.4</td>
<td>63.6</td>
<td>87.7</td>
</tr>
<tr>
<td>3.50</td>
<td>54.6</td>
<td>75.0</td>
<td>95.4</td>
</tr>
<tr>
<td>3.75</td>
<td>70.8</td>
<td>85.5</td>
<td>100.2</td>
</tr>
</tbody>
</table>
Now illustrate the summary results graphically.

- Obtain a **scatter plot** of **Ave Time in GrindQ** against **Ave Wash time**, with data points connected by lines
- Also **drag** in the **lower** and **upper confidence limits**
- The **chart** could be **formatted** to look something like this:

```
In Section 3 you will be repeatedly using the model you have been using in Section 2. For convenience specify the Trials now and also correct the average Wash time.

- Confirm that the **Warm Up Period** is **480** and the **Results Collection Period** is **2400**
- Double click on the **Washer** icon and change the **Average** time back to **2.75**
- Use / Trials / Conduct Trial, set the **Number of Runs in Trial** to **20** and the **Base Random Number Set** to **1**, then click on **OK and Run the Trial**
- Reset and Save your model (still as **Gear2**)
```
2.7 Variation in simulation experiments: summary

There are three levels of variation in simulation experiments.

(i) At the lower level there is variation between individual work items, such as the simulated queuing time or time spent in the system by each simulated work item.

(ii) At an intermediate level there is variation between different runs (within a simulation trial), such as simulated day-to-day or week-to-week variation in simulated total work items completed or average queuing time.

(iii) At the higher level there is variation between simulation trials, with different random number streams giving different simulation results, and any Simul8 trial giving a confidence interval for each theoretical long-run expected result.

If you want to read more about calculating confidence intervals, there are many suitable textbooks, such as: *Statistics for Business and Economics*, by Anderson, Sweeney and Williams, published by West.
3. ADVANCED MODELLING TECHNIQUES

In this section you will use the model that you saved as Gear2 as a basis from which to create a number of variations, illustrating the modelling of more complex behaviour.

The model building will not be progressive, as it was in previous sections, and you can select any of the following subsections for investigation in any order.

3.1 Controlling the graphical appearance of your simulation model.

In simulation, as in other types of modelling, the terms verification and validation have the following conventional meanings.

Verification is used for the process of debugging (removing errors) and ensuring that the model has the logical structure that you intended it to have.

Validation is used for the process of ensuring that the model produces results that concur with those aspects of the real system you have decided to model.

In other words, verification is about getting the model to do what you want it to do, and validation is about seeing if what you want it to do is ‘correct’.

Simul8, in common with other visual interactive simulation packages, enables you to take advantage of the graphical interface when verifying your models. Improving the appearance of your simulation model to make the graphics more informative not only helps the analyst in the verification process but also helps the client to understand the analyst’s model.

There are a number of ways in which this can be done. The methods you will look at, in order of sophistication, include

(i) Zooming in and out
(ii) Changing the icons for the basic elements of the simulation
(iii) Grouping several icons into a single icon
(iv) Changing the appearance of the icons to reflect their current status (busy, idle, etc.)
(v) Changing the appearance of the work items to reflect their current status (raw, ground, etc.)
3.1.1 Zooming in and out

Some models get too big to fit in the simulation window. Using the scroll bars will help you navigate around the model, but the zoom facility can be used to view the whole model. Illustrate these approaches as follows.

- Start with the model you saved as Gear2 and save as Gear3a
- Use the Zoom tool to change the Zoom factor from 100% to 75%
- Change the Zoom factor to 200% (so that the model no longer fits in the simulation window)
- Use the Scroll Bars to move around the (oversize) model
- Change the Zoom factor back to 100%

3.1.2 Changing the icons

It is helpful to use appropriate icons for the context of a simulation analysis. Making the model more ‘communicative’ with suitable graphics helps the analyst to keep track on the development of a model. What is more important, however, is that it helps a client to understand and be more involved in the modelling, and that it will help other analysts to take over the work if necessary.

Try this out as follows.

- Click on the Deliveries icon
  - in the Work Entry Point Properties window click on the Graphics button
  - in the Graphics window click on the displayed image
  - in the Image Editor window click on Library
  - look in some of the folders, inspecting the icons in the Preview window
  - from the old_images folder select def_i.BMP as an alternative image
  - OK back to the model
- Repeat with the Dispatch icon to change the image to def_o.BMP from the same folder
- Practise by choosing a suitable alternative image for at least one of the other icons (queue, work centre or work exit point)

Note that the images are stored in read-only files. You can edit images that you have stored in your own model, but not the source files in their folders.
You can use the Simul8 Image Editor to construct your own images. Try this out with a simple blue rectangle filled with yellow. (Drawing your own complex icons should be avoided as far as possible, as it is very time-consuming.)

- Double click on the **Wash** icon, click on **Graphics** and in the **Work Centre Graphics** dialogue box click on **Awaiting Work (Default Image)** button
- In the **Images** dialogue box change the name to **blue rectangle** then click on **New**
- In the **Simul8 Image Editor** dialogue box drag your cursor slowly over all the **Graphics tools** to find out what each of them does, noting especially
  - the **Colour Palette**
  - the **Left mouse colour**
  - the **Right mouse colour**

You left-click on any drawing tool in order to activate it. But the colour you get depends on whether you left- or right-click in the drawing area.

- Left-click on the **Left mouse colour**, drag the cursor over the palette to find a suitable **blue** then left-click to select it.
- Left-click on the **Right mouse colour**, drag the cursor over the palette to find a suitable **yellow** then left-click to select it.
- Left-click on the **Box** button then **left-click** and **drag** in the **drawing area** to produce a **blue** rectangle
- Left-click on the **Fill** button then **right-click** anywhere in the rectangle to fill it with **yellow**
- **OK** back to the model

Work items can also be changed.

- Use **/ Objects / Work Item Types** and with **Gear** selected, click on the **image** to open up the **Image Editor**
- Use the **Image Editor** to create a simple square image with suitable **name**, about the same **size**, but a different **colour**, then **OK** back to the model
- **Run** the model to observe the new icons
- **Reset** and **Save** the model (still as **Gear3a**)

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If you cannot find suitable icons for a particular context and do not want to spend too much time building very intricate icons using the graphics palette, then it would be sensible to conform approximately to these common conventional symbols:

- rectangle for all tasks (work centres in our example)
- circle or ellipse for all queues (storage areas in our example)

Rectangles are easy to draw using the graphics palette.
A red circle is available in the standard library of images.

### 3.1.3 Grouping several icons into a single icon

For large models it is often helpful to represent a group of work-centres and/or storage areas by a single icon.

To illustrate this, assume that polishing and inspection take place in the same workshop, and replace this workshop by a single icon.

- **In Gear3a** adjust the locations of the **PolishQ**, **Polish (1 and 2)**, **InspectQ** and **Inspect** icons, if necessary, to ensure that they will fit inside a rectangle that does not include any other icons
- **Click and drag**
  - from above this group on the left
  - down to below the group on the right
  so that you get a dotted line rectangle fully enclosing these icons and no others
- **Right-click** inside the rectangle and in the options list select **Create Sub-Window**
- **Close** this sub-window to collapse the window to a single icon, and use the **Show/Hide Route Arrow** button to confirm the routing to and from the group

By replacing a group of icons by a single icon, it is possible to save on-screen space when building large complex models.
The icon used to represent the group can be changed.

- Right-click on the group icon, select Sub-Window Properties and in the Window Properties dialogue box
  - give the Name as Workshop
  - click on Title, in the Simulation Object Title dialogue box select Show Title on the Simulation Window and OK back to the Window Properties dialogue box
  - double-click on the sample image and use the Library to select an alternative image (such as store.bmp in the Buildings folder)
  - OK back to the model

- Run the model, slowly at first and while the model is running double-click on the Workshop to open up the group and observe the routing of work items within the group

- Click on the Close window button (top right hand corner) to show the Workshop icon again, then increase to maximum speed to complete the simulation run

Remove the Sub-Window.

- Double click on the Workshop icon to restore the window, click once on the Control Box at the top left of the window and select Delete this Sub-Window

- Re-locate the objects from the window

- Reset and Save the model (still as Gear3a)
3.1.4 Changing the appearance of icons to reflect their current status

Allowing a work centre to change its appearance according to its status can help the model to ‘explain itself’.

Try this out by having three images for the Grind 1 icon, one for when the work centre is awaiting work, a second for when it is working and a third for when it is ‘blocked’ (ie the job is finished but the work item cannot move on because the next work centre is occupied and there is no intermediate storage space).

First look at the default image,

- Double click on the Grind 1 icon, and in the Work Centre Properties dialogue box click on the Graphics button
- In the Work Centre Graphics dialogue box click on the Awaiting Work (Default Image) button
- In the Images dialogue box, scroll down the immediately available images (default images provided by Simul8 and additional images that you have used) and inspect them in the preview box
- Click on Cancel to return to the Work Centre Graphics dialogue box and retain the current image

All four of the Animated Images (reflecting the possible different states of the work centre) use the same image unless you choose to change this. Change the images for Working and Blocked.

- In the Animated Images click on Working, from the Images list select Default Image Component, then click once on OK
- In the Animated Images click on Blocked, in the Images dialogue box click on Add from Library, select a suitable image such as no_entry.bmp from the Other folder, then OK back to the model
- Run the model slowly and observe the change in appearance as the status of the work centre changes

If a work item has finished in Grind 1 but cannot move out because Wash is occupied (and there is no queue/buffer between them) the Blocked icon will appear until the work item is able to move on.

- Reset and Save the model (still as Gear3a)
3.1.5 Changing the appearance of work items to reflect their current status

You may wish to change the appearance of work items as they go through the simulation. For instance a gear can go through states raw, ground, washed, polished and inspected.

Create graphic images associated with each different state. Keep all the new images similar in size, with variations in shape and/or colour. Don’t spend too much time creating intricate images. A suitable image would be a small square using just one colour, but be inventive if you wish. If you want something sophisticated then it is generally more efficient to select existing images from the available menu (or possibly make minor changes to copies of existing images).

- Use / Graphics / Images / New, in the Image Editor dialogue box right-click on the Left mouse colour and select More colours
- In the Colour dialogue box, click on one of the Basic colours, move the Slider (on the right of the dialogue box) to adjust the depth of colour, then click on OK

The Colour dialogue box provides more control than the Colour Palette in the Image Editor.

- In the the Image Editor use the Solid Box with the Left mouse colour tool to create a small single-colour box about the same size as the existing work item icon, give the name as ImageRaw, and OK back to the Images dialogue box
- Repeat to create different images with names ImageGround, ImageWashed, ImagePolished and ImageInspected

Use the new work item images to modify the display.

- Use / Objects / Work Item Types and click on the Select button
- In the Images list select ImageRaw, then OK back to the model

This image will now be the default image for the work item types as they arrive into the system.

- Run the model to observe the new default work item image
- For each work centre Grind 1, Grind 2 and Grind 3
  - double click on the work centre icon and in the Work Centre Properties dialogue box click on Graphics
  - in the Work Centre Graphics dialogue box click on Work Item’s Image on Exit
  - in the Images list select ImageGround, then OK back to the model
- Repeat for other work centres:
  - Wash, setting the Work Item’s Image on Exit to be ImageWashed
  - Polish 1/2, setting the Work Item’s Image on Exit to be ImagePolished
  - Inspect, setting the Work Item’s Image on Exit to be ImageInspected
- Run the model to observe the new graphics, Reset and Save the model (still as Gear3a)
Changing the appearance of the work items can be useful when building and verifying the behaviour of larger and more complex models, especially when there are alternative routes through a network and/or the paths of work items cross.

3.1.6 Multiple identical work centres

If you want to model a system with a number of identical parallel service channels (i.e., multiple identical work centres) in your model then Simul8 can do this very efficiently using replicates of a single work centre. Try this out with the two polishing work centres.

- Select Polish 2, click on the Erase button, and confirm that you want to Delete the work centre.
- Select Polish 1 and rename as Polish.
- Click on the Replicate = 1 button, in the Quick Replicate dialogue box change the Effective number of work centres to 2, then OK back to the model.
- Run the model, slowly at first then at maximum speed to complete the simulation run.
- Reset and Save the model (still as Gear3a).

This is an efficient way of setting up a simulation model with multiple work centres, and is particularly useful when you have a large number of them.

The disadvantage is that it can only be used for strictly identical parallel work centres and it does not allow you to discriminate between them. For instance, you cannot give them different distributions.

You will also see in later sections that it is possible to simulate other forms of system behaviour which depend on showing each of the individual work centres explicitly, such as routing work items into one work centre in preference to another if possible, and having one work centre break down more often or take longer to repair than another.
3.2 Interruptions (scheduled and unexpected)

Most real systems include interruptions to service, which may be scheduled stoppages for maintenance or unscheduled stoppages due to breakdown. The stoppages are defined by:

(i) the distribution of time between stoppages,
(ii) the distribution of length of stoppages.

3.2.1 Scheduled stoppages for maintenance

You will first create scheduled breaks in one of the polishing work centres.

In a real system it would be more likely that both machines would be subject to scheduled maintenance, but for the purpose of this exercise the simulated behaviour will be clearer if only one of them is subject to stoppages.

Assume that:

(i) each 8-hour working day starts at 09.00,
(ii) work centre Polish 1 is scheduled to stop for maintenance for 20 minutes every 2 hours, during time intervals 10.40-11.00, 12.40-13.00, 14.40-15.00 and 16.40-17.00,
(iii) work in progress in these work centres will stop immediately and continue after the stoppage period (although in practice it is fairly common for a job in progress to be completed before starting the maintenance).

First check the performance of the polishers if there are no scheduled stoppages and no breakdowns. This is the Simul8 default assumption, ie 100% efficiency.

☐ Open the model you saved as Gear2 and save as Gear3b
☐ Run a Trial with 20 Replicates, a Warm Up Period of 480 and a Results Collection Period of 2400 to obtain means and 95% confidence intervals for
  - the Percent of time Working results for Polish 1 and Polish 2
  - the Queuing Time Average for All items in the PolishQ
☐ Summarise your Results below

Summary of results with no interruptions:
Change the efficiency for work centre Polish 1.

- Double click on Polish 1 and in the Work Centre Properties dialogue box click on the Efficiency button
- In the Efficiency dialogue box options select Detailed
- In the When a breakdown occurs options
  - select Stop work immediately
  - click on Work Items button, ensure that the Delay completion of work on Work Items option is selected, then OK back to the Efficiency dialogue box
- Click on the Time to Repair button, and in the Length of Down Times dialogue box
  - set the distribution to be Fixed with value 20
  - OK back to the Efficiency dialogue box
- Click on the Time between Breakdowns button, and in the Time Between Down-Times dialogue box
  - set the distribution to be Fixed and the Fixed value to 100
  - in the Time or Cycles options, ensure that MTBF is selected (Mean [average] Time Between periods of Failure)
  - do NOT select the Only count busy time option
  - OK back to the Efficiency dialogue box

If MTBF is selected, this is interpreted as the time from the end of one stoppage period to the start of the next (not from the start of one to the start of the next).

If MCBF (Mean [average] Cycles Between periods of Failure) is selected, this is interpreted as the number of machines cycles (ie work items processed) before the next failure.

The ‘Only count busy time’ option assumes that the next maintenance period will begin after the work centre has actually been in operation for 100 minutes (not including idle time), which is different from the assumption here that the next maintenance period will begin after a fixed period of 100 minutes (including idle time).

Run the simulation and verify the behaviour.

- Ensure that the Time Format to Digital and move the Clock near to Polish 1 to help you observe the behaviour of the simulation run
- Modify the graphics to make it easier to see what is happening
  - select Polish 1 and click on the Graphics button
  - in the Work Centre Graphics dialogue box click on Stopped button in the Animated Images
  - in the Images dialogue box click on the Add from library button
  - from the old_images folder select STP_SGN.bmp
  - OK back to the model
- Run the simulation at visual speed, slowing the simulation from just before until just after each stoppage period (starting at times 10.40, 12.40, etc) in order to observe the behaviour of works item going through Polish 1
You should see that

(i) if there is no work item in Polish1 at the start of the stoppage period (e.g., at time 10.40) then the work centre will remain empty until the end of the stoppage period.

(ii) if there is a work item in Polish1 at the start of the stoppage period then it will not leave the work centre until some time after the end, depending on how long the simulated service time is and how much had been completed before the stoppage period.

If the behaviour is hard to follow then temporarily making the Polish distribution Fixed=6 will help, but don’t forget to change it back immediately afterwards.

Changing the graphics to reflect the state of a work centre and replacing some of the stochastic behaviour with deterministic behaviour are both worth remembering as useful verification tricks.

Check the polishing results.

- Run a Trial, with the same specifications as before, to obtain means and 95% confidence intervals for
  - the Percent of Time Working results for Polish 1 and Polish 2
  - the Queuing Time Average for All items in the PolishQ

- Summarise your Results below and comment on
  - the comparison between the Percent of Time Working for the two Polish work centres in this simulation
  - the comparison between these PolishQ average queuing time results with interruptions and the PolishQ average queuing time results you recorded when there were no interruptions

- Reset and Save (still as Gear3b)

Summary of results with scheduled interruptions:

You should find that more of the work is being done by Polish 2, and the average waiting time in PolishQ has increased.
3.2.2 Unscheduled stoppages due to breakdowns

Now change to unscheduled stoppages.

Assume that :

(i) there are no scheduled stoppages for maintenance on work centre Polish 1,
(ii) breakdowns occur randomly with average time between breakdown 2 hours,
(iii) the distribution of repair time is Normal with mean 20 minutes and standard deviation 5 minutes,
(iv) the distribution of time before next breakdown (from end of each breakdown to start of the next) is Exponential with mean 100 minutes (giving one breakdown every 2 hours on average).

Modify the simulation model.

- Double click on Polish 1 and click on the Efficiency button
- Change the Time to Repair distribution to Normal with average 20 and standard deviation 5
- Change the Time between Breakdowns distribution to Exponential with average 100
- OK back to the model

Observe the operation of the model then use a Trial to collect polishing results.

- Run the simulation slowly to check the behaviour then at maximum speed to finish quickly
- Run a Trial as before to obtain means and 95% confidence intervals for
  - the Percent of Time Working results for Polish 1 and Polish 2
  - the Queuing Time Average for All items in the PolishQ
- Summarise your Results below, and compare these results (with unscheduled stoppages/breakdowns) with the previous results (with scheduled stoppages)
- Reset and Save (still as Gear3b)

Summary of results with interruptions and comparison with previous results:

Since the overall proportion of down-time for Polish 1 has not changed you should find that the distribution of effort between the two work centres is roughly the same (but with some variation due to the random behaviour). However the increase in stochastic behaviour (uncertainty) in the system should increase the queuing time.
3.3 Other methods of defining distributions

Two methods of defining distributions are covered in this section, namely empirical (which means the frequency distribution of sample data) and time-based (in which the distribution is different for different periods of the day). You will illustrate the use of these by:

(i) initially by assuming that work items arrive in variable size batches, using a discrete empirical distribution,
(ii) then by assuming that the inspection time follows a continuous empirical distribution,
(iii) and finally assuming that the arrival rate of batches of work items changes during the course of the working day.

3.3.1 Sampling from empirical distributions

Empirical distributions can be used when no obvious and easy theoretical distribution is found to fit the observed data. Empirical distributions can discrete or continuous.

3.3.1.1 A discrete empirical distribution

An example of a discrete empirical distribution is provided by random arrivals of gear mouldings in batches of variable size (whereas in Section 2 you initially assumed batches of fixed size 15 arrived at an average rate of 1 per hour, then changed this to single items arriving at an average rate of 15 per hour).

You will now assume that:

(i) batches arrive randomly at an average rate of 5 per hour (ie exponential distribution of inter-arrival time with average 12 minutes),
(ii) batch size varies according to the distribution below.

<table>
<thead>
<tr>
<th>Batch size:</th>
<th>1 2 3 4 5 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative frequency:</td>
<td>5% 45% 20% 15% 10% 5%</td>
</tr>
</tbody>
</table>

This gives an average batch size of just less than 3.
With an average of 5 batches per hour and average batch size approximately 3, the overall rate of arrival of work items will be slightly less than 15 per hour.
Define the distribution type and set up the correct number of discrete values.

- Start with the model you saved as Gear2 and Save as Gear3c
- Use / Objects / Distributions / New, define the Name as Batch Size, select Probability Profile then Next>>
  You will see a frequency distribution with 10 columns, an empty one at each end and 8 columns of data in between.
- Confirm the (default) distribution type is Discrete (rather than Continuous)
- Remove one of the non-empty columns by Right-clicking on it and selecting Delete from the options list
- Repeat so that you have six non-empty columns and an empty interval each end
  If you remove too many you can insert extra columns in a similar way.

Start to enter the distribution data.

NB - DO NOT click on OK or press Enter until all columns have been defined.

- Click on the left-hand empty column, then change the Value to 0
- Click on the first non-empty column, change the Percent (the relative frequency) to 5 and the Value (the batch size) to 1
- Click back on the first non-empty column
  The colour changes to red, showing that this Percent is Locked, whereas the others are all still Unlocked and have been adjusted to make the Percent total come to 100%.
  The new Percent value will be displayed at the top of the column, but the value is not displayed.

Enter the remaining data.

- In the 2nd non-empty column change the Percent to 45 and the Value to 2, then click back on the column to Lock the percentage
- In the 3rd non-empty column change the Percent to 20 and the Value to 3, then click back on the column to Lock the percentage
- In the 4th non-empty column change the Percent to 15 and the Value to 4, then click back on the column to Lock the percentage
- In the 5th non-empty column change the Percent to 10 and the Value to 5, then click back on the column to Lock the percentage
- In the right-hand non-empty column, change the Value to 6 (the Percent will have already been calculated as 5 from the others), then Right-click on the column and select Lock in the options list
- Click on the right-hand empty column and change the Value to 7
- OK back to the model
Before making the changes to the arrivals, check the results for the GrindQ and the InspectQ storage areas.

- Run a **Trial** with 20 Replicates, a **Warm Up Period** of 480 and a **Results Collection Period** of 2400, to obtain means and 95% confidence intervals for
  - the **Average Queuing Time** for All items in **GrindQ**
  - the **Average Queuing Time** for All items in **InspectQ**

- Summarise your **Results** below

<table>
<thead>
<tr>
<th>Summary of results:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

Change the distribution of time between arrivals to Exponential with mean 12 minutes (ie random arrivals at an average rate of 5 per hour) and replace the fixed distribution of batch size with this new Probability Profile, then run the model and collect results again.

- Double click on the **Deliveries** icon
  - change the **Distribution** to **Exponential** with **Average** equal to **12**
  - click on **Batching** and change the **Distribution** to **Batch Size**
    (user-defined distributions appear at the bottom of the list)
  - **OK** back to the model

- **Run** the model initially at slow speed then at higher speed, to look for any gross errors in the changes you have made

- Run a **Trial** as before to obtain means and 95% confidence intervals for
  - the **Average Queuing Time** for All items in **GrindQ**
  - the **Average Queuing Time** for All items in **InspectQ**

- Summarise your **Results** below and compare the **new** GrindQ result with the **previous** GrindQ result.

<table>
<thead>
<tr>
<th>Summary of results with variable batch arrivals and comparison of new GrindQ result with previous GrindQ result:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>
The change in average waiting time in GrindQ is the result of the trade-off between two conflicting effects

(i) The overall average arrival rate is slightly reduced. All other things being equal, the reduction in average arrival rate would tend to reduce average waiting times, especially close to the work item arrival point (i.e., in GrindQ).

(ii) There is now more variability in time between arrivals. For example, a batch of four work items means that there are three inter-arrival times of zero and the average non-zero time between arrivals has increased. All other things being equal, the increase in stochastic behaviour (i.e., more uncertainty) caused by the batching would tend to increase average queuing time.

You should find that the second of these dominates the first, resulting in a net increase in average waiting time in the GrindQ storage area.

### 3.3.1.2 A continuous empirical distribution

An example of a continuous empirical distribution is provided by variable inspection time. Assume that 200 inspections have been recorded and summarised in a frequency table as follows:

<table>
<thead>
<tr>
<th>Inspection time (minutes):</th>
<th>0 - 2.5</th>
<th>2.5 - 5.0</th>
<th>5.0 - 7.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of inspections:</td>
<td>109</td>
<td>83</td>
<td>8</td>
</tr>
</tbody>
</table>

The estimated average inspection time is now slightly less than 2.5 minutes.

In SIMUL8, it is possible to sample from a continuous empirical distribution, assuming that data are uniformly distributed within each interval, instead of using one of the standard (continuous) statistical distributions. (This is a better assumption if the data are more finely divided into narrower class intervals.)

The continuous empirical distribution should be defined in terms of the relative frequencies and upper limits of each class interval, including an empty class interval at each extreme. So the frequency distribution should be given as:

<table>
<thead>
<tr>
<th>Upper limits:</th>
<th>0</th>
<th>2.5</th>
<th>5.0</th>
<th>7.5</th>
<th>10.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative frequency:</td>
<td>0%</td>
<td>54.5%</td>
<td>41.5%</td>
<td>4.0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Define the distribution type and set up the correct number of discrete values.

- Use /Objects / Distributions / New, define the Name as Inspect Time, select Probability Profile, then Next>>
- Change the distribution type from Discrete (the default type) to Continuous
- Remove one of the non-empty columns by Right-clicking on it and selecting Delete from the options list, then repeat until you have three non-empty columns and an empty interval at each end
Now enter the distribution data.  
**NB**: DO NOT click on OK or press Enter until all columns have been defined.

- Click on the left-hand empty column, and change the Value to 0 (the upper limit of the interval from -2.5 to 0)

  The upper limit of the first (empty) interval is essential, because it defines the lower limit of the next (non-empty) interval.

- Click on the left-hand non-empty column, change the Percent value to 54.5 (the relative frequency for this interval) and the Value to 2.5 (the upper limit of the interval from 0 to 2.5), then click back on the column

  This will automatically select the Lock option for the column you have just changed.  The other columns are currently Unlocked.

- Click on the next column, set the Percent for the second non-empty column to 41.5 and the upper limit Value to 5, then click back on the column

- Click on the third non-empty column, set the upper limit Value to 7.5, check that the Percent has been adjusted to 4 (to make the total come to 100), then Right-click on the column and select Lock in the options list

- Click on the right-hand empty column and change the Value to 10

  Any number greater than 7.5 would be OK for the right-hand empty column.

- Finally, OK back to the model

  Note that the distribution is assumed to be uniform, ie level, within each interval in the continuous empirical distribution.  The red lines that appear on the chart are for illustration only, to remind the user that it is not a discrete distribution, and the fact that they are sloping does not imply that the probability varies across any interval of the continuous empirical distribution.

Keeping the revised arrival rate and empirical distribution of batch size, replace the exponential distribution of inspection times with your new continuous empirical distribution, then run the model and collect results.

- Select the Inspect work centre and change the distribution to Inspect Time, then OK

- Run the model at slow speed initially to look for any gross errors in the changes you have made, then at maximum speed

- Run a Trial with the same specifications as before to obtain means and 95% confidence intervals for
  - the Average Queuing Time for All items in GrindQ
  - the Average Queuing Time for All items in InspectQ

- Summarise your Results in the following table, and compare the new InspectQ average (with the revised distribution) with the previous InspectQ average

- Reset and Save (still as Gear3c)
Summary of results with variable batch arrivals and empirical distribution of inspection times:

You should not find any significant change in average queuing times for the grinding work centres, but there should be some reduction in the average queuing times for inspection because now there is not only a small reduction in the average inspection time but also less variability in the inspection times.

3.3.2 Time dependent distributions

This SIMUL8 facility is very useful for systems that never reach a steady state. For instance you may wish to simulate arrivals with rates which vary over a regular daily cycle.

The model you have developed in section 3.3.1 assumes that batches (of average size approximately 3) arrive at an average rate of 5 per hour.

Now assume that the factory works a 7-hour, 6-day week, with each simulation run equivalent to one working week. You will make the arrivals time-dependent, with an average arrival rate of:

- 2 batches per hour from 09:00 (the shift start time) to 10:00, ie mean inter-arrival time is 30 minutes
- 8 batches per hour from 10:00 to 14:00, (busy mid-shift period), ie mean inter-arrival time is 7.5 minutes
- 2 batches per hour from 14:00 to 16:00 (the shift finish time). ie mean inter-arrival time is 30 minutes

On average this gives
- 2 batches in the interval 09.00-10.00,
- 32 batches in the interval 10.00-14.00
- 4 batches in the interval 14.00-16.00
ie on average 38 batches per 7 hours.

With average batch size of 3, this is equivalent to approximately 38x3=114 per 7 hours, in other words just over 16 per hour. So the new time dependent arrival rate averages out slightly more than the original arrival rate (15 per hour), but this does not exceed the capacity of the system.

To cope with the higher arrival rate during the busy part of the day, assume that the GrindQ storage capacity is increased to 50.
With the increased arrival rate during the middle of the day being greater than the processing capacity of the system, the queues will tend to build up. However these can be cleared during the periods when arrivals are less frequent.

<table>
<thead>
<tr>
<th>Times when queue tends to increase</th>
<th>Times when queue tends to decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 ... 300 minutes</td>
<td>300 ... 480 minutes</td>
</tr>
<tr>
<td>480 ... 720 minutes</td>
<td>720 ... 900 minutes</td>
</tr>
<tr>
<td>900 ... 1140 minutes</td>
<td>1140 ... 1320 minutes</td>
</tr>
<tr>
<td>1320 ... 1560 minutes</td>
<td>1560 ... 1740 minutes</td>
</tr>
<tr>
<td>1740 ... 1980 minutes</td>
<td>1980 ... 2160 minutes</td>
</tr>
<tr>
<td>2160 ... 2400 minutes</td>
<td>2400 ... 2520 minutes</td>
</tr>
</tbody>
</table>

Change the clock settings.

- Start with the model you saved as Gear3c
- Use /Clock / Clock Properties and in the Clock Properties dialogue box confirm that the Time Units are Minutes
- In the Days options, select Day and set the Days per Week to 6
- In the Time Format options select Digital, with Start Time each day set to 09:00 and Time in each Day set to 07:00
- Click on the Warm Up Period button, set this to 0 and click on OK back to the Clock Properties dialogue box
- Click on the Results Collection Period button, set this to 2520 and OK back to the model

You will have no warm-up period and a results collection period of one week. This will give a total of 60(min/hr)x7(hrs/day)x6(days/wk) = 2520 minutes.

Define the component distributions, Arrivals 1 (with mean inter-arrival time 30 minutes, ie mean arrival rate 2 per hour) and Arrivals 2 (with mean inter-arrival time 7.5 minutes, ie mean arrival rate 8 per hour)

- Use /Objects / Distributions /, click on New, define the Name as Arrivals 1, set the Type of Distribution to be a Named Distribution and click on Next>>
- In the Named distribution dialogue box set the Distribution to Exponential, set the Average time between arrivals to 30, then OK back to the Distributions dialogue box
- Create another New distribution, named Arrivals 2 to be a Named Distribution which is Exponential with the Average time between arrivals set at 7.5, then OK back to the Distributions dialogue box
Now you can define the time dependent distribution, which take the identity Arrivals 1 or Arrivals 2 depending on the time of the day.

- Create another **New** distribution, named **Arrivals** to be **Time Dependent**
  then click on **Next>>**

- In the **Time Dependent Distribution** dialogue box click on the **Add** button

- In the **Time Slot..** dialogue box define the time as **from 09:00** and the distribution as **Arrivals 1**, then click on **OK**

- **Repeat** to define the distribution from **10:00** as **Arrivals 2**

- **Repeat** to define the distribution from **14:00** as **Arrivals 1**

- **OK** back to the model

- Double click on the **Deliveries** icon and in the **Work Entry Point Properties** dialogue box set the **Distribution** to **Arrivals**

Allow more work items to be stored in the queue for the grinders, run the model and observe the GrindQ store over time.

- Click on **GrindQ**, and in the **Storage Bin Details** dialogue box change the queue **Capacity** to **50**, then click on **OK**

- With **GrindQ** selected, click on the **Make Time Graph...** tool and stretch the empty graph across the screen

- Ensure that the **Time Format** to **Digital** and move the **Clock** near to **GrindQ** to help you observe the behaviour of the simulation run

- **Run** the model slowly at first to inspect the arrival behaviour and the number of items in **GrindQ**, then increase to maximum to complete the simulation run, and inspect the **queue length time graph**

- Use / **Clock** / **Change Random Nos and Run** a few times and each time inspect the plot of queue length against time

Only the simulated shift periods (7 hours each day) are represented on the plot of queue length against time, and the non-working hours (17 hours each day) are suppressed.

You should notice a tendency for the queue length to increase during the periods of faster arrivals (in the middle of each day) and to reduce during periods of slower arrivals.

- Roughly sketch the last **Time graph** below, and comment on the main features

- **Reset** and **Save** (still as **Gear3c**)
3.4 Processes, Prioritising and Routing

In many processes one machine may be preferred to an alternative machine. Also the outcome from any machine may not be 100% perfect. For example, many processes produce defective items that may need to be re-worked or, in extreme cases, scrapped. You will illustrate these possible scenarios in the gear production model:

(i) initially by assuming that grinding is to be done on Grind 1 whenever it is available, on Grind 2 if possible when Grind 1 is not available, and on Grind 3 if neither of the others is available,

(ii) then by assuming that 4% of gears break on the grinding machines and are scrapped,

(iii) then by assuming that on inspection 5% are sent back to be re-polished,

(iv) and you will finally assume that 2% of work items are sent back for re-grinding by the operator who takes them from the grinding work centres, in order to see how to deal with the problem of recycling work items into the same work centre they have just left.

This is shown in the flow diagram below:
3.4.1 Prioritising the work centres

Where there are a number of work centres working in parallel, it is common to have a priority rule. In this case assume that Grind 1 is the most preferred grinding work centre and Grind 3 the least preferred.

In Simul8 each work centre has a priority level which can take any value from 0 (lowest) to 100 (highest), and by default the priority is set to 50. So to model this particular priority rule the value for Grind 1 can be increased to 60 and for Grind 3 it can be reduced to 40. Work items will then be routed to whichever unoccupied grinding work centre has the highest priority level. (The actual values are arbitrary, provided that Priority 1 > Priority 2 > Priority 3).

Assign priorities to the grinding work centres.

- Open the saved file called Gear2 and Save as Gear3d
- Double click on the Grind 1 icon, then click on the Priority button
- In the Priority dialogue box ensure the Priority Method is Fixed and increase the Priority Level from the default value of 50 to 60 then OK back to the model
- Repeat for Grind 3 but this time reduce the Priority Level to 40
- Confirm that for Grind 2 the Priority Level is still 50

Check the operation of your model then collect utilisation results for the work centres.

- Run the model initially at slow speed to check the operation then increase the speed to finish the run
- Reset and Save the model as Gear3d

You should observe that work items only go to Grind 2 when Grind 1 is occupied, and only go into Grind 3 when both Grind 1 and Grind 2 are occupied

- Run a Trial with 20 Replicates, a Warm Up Period of 480 and a Results Collection Period of 2400, to obtain means and 95% confidence intervals for - the Percent of Time Working for Grind 1, Grind 2 and Grind 3
- Summarise your Results below

Summary of results:
You should have found that the differentiated priorities are reflected in your results. The differences in percentage occupancy should be greater if there are fewer work items arriving (so that there is less chance of Grind 1 being occupied).

Try this out with only half the current average arrival rate. This is 7.5 per hour (average inter-arrival time 8 minutes) instead of 15 per hour (average inter-arrival time 4 minutes).

- Double click on the Deliveries icon, change the Average time between arrivals to 8, then click on OK
- Run a Trial, with the same specifications as before, to obtain means and 95% confidence intervals for
  - the Percent of Time Working for Grind 1, Grind 2 and Grind 3
- Summarise your Results below and check that they are as expected

Summary of results:

- Change the Average time between Arrivals back to 4
- Reset and Save the model (still as Gear3d)

3.4.2 Sending to scrap

You will now assume that 4% of gears break on the grinding machines and are scrapped. First create a new work exit point for the scrapped material and put in routes from the grinders and this new work exit point. Your model will look something like the one below.
Create the scrap bin with routing arrows from the Grind work centres.

- Use the Create Work Exit Point tool and place the new icon below Wash
- Change its name to Scrap Bin and use the Graphics options to display Image+Count and Title
- Insert routes from Grind 1, Grind 2 and Grind 3 to the Scrap Bin

Change the output from the Grind work centres to send 4% to scrap.

- Double click on the Grind 1 icon and then the Routing Out button
- In the Routing Out From dialogue box first run the cursor slowly over the Discipline options list to see the explanations for each, then choose the Percent option
- Leave the Ignore Blocked Routes option Off

If the Ignore Blocked Routes option is used then whenever the grinders cannot send items to the washer because it is busy they will try another available route (ie send them instead to the scrap bin). This is not what you want!

- In the list of destinations click on Wash and in the Percent value box enter 96
- Change the Scrap Bin percentage to 4 in the same way and OK back to the model
- Repeat the above process for Grind 2 and Grind 3

Check the operation of your model then obtain results for the number of work items going to Scrap Bin and Dispatch.

- Run the model initially at slow speed to check the operation then increase the speed to finish the run

You should observe that work items are occasionally sent to the Scrap Bin instead of the washer.

- Run a Trial as before to obtain means and 95% confidence intervals for - the Work Completed in the Scrap Bin work exit point
  - the Work Completed in the Dispatch work exit point

- Summarise your Results below

You should be able to confirm that approximately 4% are sent to the Scrap Bin.

- Reset and Save the model (still as Gear3d)

Summary of results:
3.4.3 Sending back to a preceding work centre with priority treatment

In this subsection you will see how a work centre can accept work items from different queues and, where appropriate, give items from one queue a higher priority than those from the other queue.

Assume that the Inspection process identifies 5% substandard polished gears that need re-polishing.

If you route them back into the PolishQ storage area then when PolishQ is full to capacity the simulation will allow substandard polished gears to block the Inspection channel because they have no-where to go to. This is not logical, so create another storage area called RepolishQ.

Assume that this will only serve one of the Polish work centres (Polish 2), and that the re-cycled substandard gears will be given a higher priority than washed gears which have not been recycled. This can be achieved using the Routing In option in the Polish 2 work centre. (An alternative method of prioritising the recycled items is described in Section 3.6)

Your model will look something like the one below.
Modify the model.
- In the model you saved as Gear3d, create a new storage area with unlimited capacity below PolishQ, name the new storage area as RepolishQ and use the same graphics options as the other queues.
- Put in Routing Arrows from Inspect to RepolishQ, and from RepolishQ to Polish 2, and adjust the location of icons, if necessary, to improve the layout.
- Click on the Inspect work centre and change the Routing Out to send 5% back to RepolishQ and 95% to Dispatch.
- Select the Polish 2 work centre and click on the Routing In button.
- In the Routing In To dialogue box ensure that the Selection Method tab is selected and that the Discipline is Priority.
- To change the order of priority in the list of routes in to the work centre, click on one of the routes in, then use the Up / Down buttons to change its position in the list so that the items from RepolishQ have the higher priority.
- OK back to the model.

Check the operation of your model then use a Trial to collect results.
- Run initially at slow speed to check the operation then increase the speed to finish the run.
- Run a Trial as before to obtain means and 95% confidence intervals for
  - the Percent of Time Working for Polish 1 and Polish 2
  - the Total Entered for RepolishQ
  - the Work Completed for Dispatch
- Summarise your Results below.

You should be able to confirm that approximately 5% of finished work items were sent back for repolishing, and that Polish 2 is utilised slightly more than Polish 2.
- Reset and Save (still as Gear3d)

Summary of results:
3.4.4 Routing back to the same work centre

Re-cycling work items back from a work centre to its own queue can be achieved using a dummy work centre which takes zero time to perform its task before sending work items back to the queue.

Assume that, after grinding, 2% of work items need to be sent back for re-grinding.

For the sake of simplicity assume that the reprocessing time has the same distribution as the original processing time.

Your model should look something like the one below.

Set up the new routes.
- Use the Create Work Centre tool to place a new work centre near to the GrindQ icon, rename it as Dummy 1, and make the distribution Fixed with Fixed Value = 0.
- Draw routes from Grind 1, Grind 2, and Grind 3 to Dummy 1.
- Draw a route from Dummy 1 to GrindQ.
- In work centre Grind 1 ensure that the Routing Out discipline is still set to Percent (with the Ignore Blocked Routes option NOT selected).
- Adjust the Percentages to send 94% to Wash, 4% to Scrap Bin and 2% to Dummy 1.
- Repeat for Grind 2 and Grind 3.

The model may now appear to have all the correct properties. However there is still a problem, which is illustrated by collecting some results.
Collect results to check the operation of this model.

- Check the **Routing In** options for **Dummy 1** and **Wash**

You will find that the default **Discipline** in each is **Priority**, which is not what is required.

To illustrate what goes wrong if this is not changed, run this current model before correcting it.

- Using a **Warm-Up** period of **480** minutes and a **Results Collection Period** of **2400** minutes, **Run** initially at slow speed to check the operation then increase the speed to finish the run

- Double click on the **Dummy 1** icon, click on the **Results** button, and note the number of **Completed Jobs**

Completed Jobs in Dummy 1 are the recycled work items. The number recycled will be much higher than 2% of the number entering the system (displayed over the Deliveries icon). This accounts for the increase in queuing in QrindQ.

So why should the proportion of work items recycled through the dummy work centre be so much more than the intended 2% of those entering the system?

The problem is that if a work centre directly feeds another work centre without an intermediate storage area then there may be a conflict between the upstream Routing Out rule and the downstream Routing In rule. That is what is going wrong here.

You have seen in a previous sub-section that the Priority Routing In rule enables alternative downstream work centres to ‘compete’ for work items. A side effect in this model is that Dummy 1 ‘grabs’ any work item emerging from Grind 1, 2 or 3 if the Wash work centre is occupied.

So the Dummy 1 (downstream) Priority Routing In rule interferes with the Grind 1, 2 & 3 (upstream) Percent Routing Out rule, and far more than 2% of work items are recycled.

Either of the following two methods will resolve the problem.

(i) Change the (downstream) Dummy 1 Routing In option to Passive, which allows the (upstream) percentage Routing Out option to operate without interference.

(ii) Prevent Dummy 1 from competing for work items from Grind 1, 2 & 3 by inserting a dummy queue before Dummy 1 (since a queue is always effectively ‘passive’ and can’t compete for work items).

The first method draws attention to why the problem arises.

The second method illustrates good practise in model building. In general you should always insert a queue between successive work centres (whether ‘real’ or ‘dummy’) unless you have a good reason to omit it. The absence of a storage area before the Wash work centre in the actual system would, of course, be good reason not to have one in this model.
Use the first method, modifying the Dummy1 Routing In options.

- Click on the **Dummy 1** icon then on the **Routing In** button
- In the **Discipline** options select **Passive**, then **OK** back to the model

Now the Dummy 1 work centre will not compete for work items emerging from Grind 1, 2 or 3 when Wash is occupied.

It is not necessary to change the Wash Routing In option. Wash never has the opportunity to ‘grab’ work items from Dummy 1 when the latter is occupied, because Dummy 1 has zero duration.

- **Run** initially at slow speed to check the operation then increase the speed
- **Run a Trial** as before to obtain means and 95% confidence intervals for
  - the **Completed Jobs** for **Dummy 1**
  - the **Work Completed** for **Scrap Bin**
  - the **Work Completed** for **Dispatch**
- **Summarise** your **Results** below

You should now find that about 2% of the total work completed have been recycled through Dummy 1 and about 4% have been sent to the Scrap Bin.

<table>
<thead>
<tr>
<th>Summary of results:</th>
</tr>
</thead>
</table>

Use the second method, inserting a dummy queue before the dummy work centre.

- **Delete the** **Routing Arrows** from **Grind 1, 2 & 3** to **Dummy 1**
- **Insert a dummy storage area** before **Dummy 1**, with name **Dummy1Q** and with the same **graphics** as the other storage areas
- **Insert Routing Arrows** from **Grind 1, 2 & 3** to **Dummy1Q**, and from **Dummy1Q** to **Dummy 1**
- **Set** the **Percentage Routing Out** from **Grind 1, 2 and 3** to be **94% Wash, 4% Scrap Bin, 2% Dummy1Q**
- **For** **Dummy 1**, reset the **Routing In** as **Priority**

This will demonstrate that the dummy queue now prevents the Dummy 1 work centre from ‘grabbing’ work items, regardless of the (default) Priority Routing In.

- **Run a Trial** with the same random number streams as before, collect **Results** as before, and summarise below

With the same random number streams you should get the same results as before.

- **Reset** and **Save** (still as **Gear3d**)

| Summary of results: |
3.5 Resources

Frequently a resource is required to set up a process, or to reset a machine after processing a work item. In this section you will use an operator to mount each gear on the grinding machine, as follows:

(i) you will define a single resource (operator) to attend to the grinders, then make the operator responsible for setting up each gear at the start of grinding,
(ii) then you will need to make further use of resources to ensure that a gear cannot be set up on a machine before the previous one has been finished.

3.5.1 Using an operator at the grinders

Because there is only one operator he will float between the grinding machines. Assume that the set up times (including any travel time between machines) are Normally distributed with mean 1 minute and standard deviation 0.2 minutes, and that the actual processing times are Exponentially distribution with mean 9 minutes (so the mean combined time is still 10 minutes).

Before making any changes, check the results for average waiting time in the GrindQ store.

- Start with the model Gear2 and save as Gear3e
- Run a Trial with 20 Replicates, a Warm Up Period of 480 and a Results Collection Period of 2400, to obtain means and 95% confidence intervals for
  - the Queuing Time Average for All items in GrindQ

You will now revise the start of your model to look something like this:
Define the distribution for setup and the new distribution for grinding.

- Use / Objects / Distributions, in the Distributions dialogue box click on New and change the name to SetupDist
- Define the type of distribution as a Named distribution, and click on Next>>
- In the Named Distribution dialogue box define it as a Normal distribution with Average = 1 and Standard Deviation = 0.2 and OK back to the Distributions dialogue box
- In the Distributions dialogue box select GrindDist and click on Properties
- In the Named Distribution dialogue box keep the Distribution type as Exponential, change the Average to 9, and OK back to the model

This automatically updates the distribution for all three grinding work centres.

Create an operator as a resource.

- Click on the Create Resource icon on the toolbar and position the resource (the operator) somewhere close to the Grind work stations
- Double click on this Resource, change the name to Operator and the Number of this type of resource available to 1
- Click on the Travel button and in the Resource Travel Times dialogue box
  - confirm that the travel Time from any Work Centre location to any other Work Centre location is = 0 minutes
  - OK back to the Resource Properties dialogue box
- Click on the Graphics button and in the Graphics dialogue box
  - Select the Display Style as Image+Count
  - Click on the Title button, in the Simul8 Object Title dialogue box select Show Title on Simulation Window, then OK back to the Graphics dialogue box
  - Click on the graphics image and in the Image Editor dialogue box click on the Library button
  - Select a suitable image from the list such as topview1h.bmp in the People folder
  - OK back to the model
A quick way of putting in three identical Setup work centres is to remove the routing arrows from GrindQ, create one work centre with appropriate properties (including the required distribution and resource assignment), copy it, then put in the new routing arrows.

Create a Setup activity (modelled as another work centre) before the Grind 1 work centre and assign the operator to the new task.

- Use **Shift** and **click and drag** from source to destination each time to remove the **Route Arrows** from **GrindQ** to each **Grind** work centre
- Use the **Create Work Centre** tool to put a new work centre before **Grind 1**
- Double click on the **new Work Centre**
  - change its name to **Setup 1**
  - set the **Distribution** to be **SetupDist**
  - give it the same **Graphics** properties as **Grind 1**
- Double click on **Setup 1** and click on the **Resources** button
- In the **Resource Required** dialogue box
  - click on the **Add** button
  - from the **Resource Objects** list select **Operator**
  - click once on **OK**
- In the **Resource Required** dialogue box ensure that both the following options are selected
  - **Require resources before collecting any work item**
  - **Release resources as soon as task complete**
- **OK** back to the model

Create two more Setup work centres with identical properties, and put in the required route arrows.

- To create a new work centre **Setup 2** with the same properties as **Setup 1**, hold down the **Ctrl** key then **Click and Drag** from **Setup 1** to a new location before **Grind 2**
- **Repeat** to create another new work centre **Setup 3** with the same properties, located before **Grind 3**
- Use **Shift/click and drag** to create **Route Arrows** from **GrindQ** to each **Setup** work centre, and from each **Setup** work centre to its corresponding **Grind** work centre
- Confirm that the resource **Operator** is required by **Setup 2** and **Setup 3**
To check the new model, ‘step through’ the simulation process, which means successively moving the simulation clock on to the time of each ‘next event’.

- Click once on the Step button

You should observe that
- the first work item arrives into the GrindQ storage area and immediately moves into work centre Setup 1 (the utilisation value over the Setup 1 icon changes to 1),
- the resource Operator is assigned to that work centre (the number available over the resource icon changes from 1 to 0).

- Click on the Step button a few more of times

You should observe that each time the ‘next event’ entails the start of another Setup task, the resource Operator is assigned to the appropriate work centre.

This model is not yet correct because both the setup of a new work item in a work centre and grinding of the previous work item in the same work centre can take place simultaneously. This can be seen, for example, when the numbers above Setup 1 and Grind 1 each show that the utilisation is 1.

Collect results for this provisional model (which you will improve in the next sub-section).

- Run a Trial, with the same specifications as before, to obtain means and 95% confidence intervals for
  - Average queuing time for All items in GrindQ
  - the % Utilisation of the Operator

- Summarise your Results below

- Reset and Save (still as Gear3e)

Summary of results

You should find that allowing a job to start in a Grind work centre before the previous job has finished significantly reduces the average waiting time in GrindQ.

### 3.5.2 Improving the model

The provisional model allows the setup to proceed even when a previous work item is being processed in a grinding work centre. There may be some systems that can be correctly modelled in this way. However, in most systems the setup cannot begin until the machine is free after the previous work item and it is assumed that this is the type of system that you want to model.
To model the system correctly it is useful to think of ‘Setup’ and ‘Grind’ as activities or tasks, rather than work centres, then define a resource called, for example, ‘Grinder’ which is required by each of these tasks.

Create three resources to represent the grinding work centres.

- Start with the model you saved as Gear3e, click on the Create Resource icon and position the resource near Grind 1
- Double click on this resource, change the name to Grinder 1 and the Number of this type of resource available to 1
- Use the Graphics options to display Image+Count and Title
- Use the Library to select a suitable icon such as Machine6a.bmp in the Manufacturing folder
- Hold down the Ctrl key and drag on Grinder 1 to create an identical resource Grinder 2, and repeat to create Grinder 3
- Assign the resource Grinder 1 to both Setup 1 and Grind 1
- Assign the resource Grinder 2 to both Setup 2 and Grind 2
- Assign the resource Grinder 3 to both Setup 3 and Grind 3

To check the new model, then collect results.

- Click once on the Step button
  When the first work item arrives into the GrindQ storage area and then immediately moves into work centre Setup 1, both resources Operator and Grinder 1 are assigned to that work centre.
- Click on the Step button a few more of times
  For each grinding centre, the use of the Grinder resource means that either the setup operation or the grinding operation can be utilised at any time, but not both.
- Run a Trial, as before, to obtain means and 95% confidence intervals for
  - the Average Queuing Time for All items in GrindQ
  - % Utilisation of the Operator
- Summarise your Results below
- Reset and Save the model (still as Gear3e)

You should find that the average waiting time in the GrindQ storage area is now greater than in the provisional model which erroneously allowed any Grind work centre to begin the Setup operation with a new work item while simultaneously finishing the grinding of a previous work item.

Summary of results:
3.6 Labels

More control can be exercised over the operation of the simulation model using labels attached to work items. These are sometimes referred to as attributes.

Labels can be attached to work items either when they enter the simulation or at any point within it. The value of the label can be tested and/or changed at any work station.

Labels can be of two types, numeric or text.

(i) **Numeric Labels** are mainly used to prioritise work items within a queue or to control the flow of work around the simulation.

(ii) **Text Labels** are mainly used to allow different distributions to be used within the same work centre.

(iii) **Both types** can be used to control the appearance of work items.

3.6.1 Using a numeric label to prioritise work

There may be work items entering the work-flow as urgent jobs, which move ahead of non-urgent jobs in queues. Although you are giving priority access to the work centres you don’t achieve this by editing the work centres - it is in the queues that the simulation controls the priorities by allowing higher priority items to “jump the queue”.

This behaviour can be modelled using separate work entry points, with the urgent and non-urgent jobs each arriving with their own distributions of inter-arrival times and different levels of urgency.

Different priority levels for items entering work centres could in fact be achieved more simply by putting the different items into separate queues and using the Routing-In by Priority option in the work centre. (This is described in section 3.4.3).

However, once they have passed through that work centre it would not be possible to distinguish between the different work items in order to assign priorities at the next work centre. Furthermore it would not be possible to obtain separate result summaries for the different categories of work items. Both of these can be achieved using a numeric label.

You will assume that the combined average arrival rate will still be 15 per hour, with 80% of jobs non-urgent and 20% urgent.

- For non-urgent items the average arrival rate will be 12 per hour (80% of 15 per hour) so the average inter-arrival time will be 5 minutes.
- For urgent items the average arrival rate will be 3 per hour (20% of 15 per hour) so the average inter-arrival time will be 20 minutes.
Define a numeric label called Urgency and attach this label to the work item Gear.

- Start with the model you saved as Gear2 and save as Gear3f
- Use / Objects / Labels, and in the Labels dialogue box click on New
- In the Label Properties dialogue box name the label as Urgency and accept the Type as Number, then OK back to the model
- Use / Objects / Work Item Types, and in the Work Item Type dialogue box which contains the Gear work item, click on Add
- In the List of all Labels... click on Urgency, then OK back to the model

The value of the label attached to each work item will determine its priority level. The actual values are arbitrary provided the urgent value is higher than the non-urgent value.

Modify the Work Entry Point to generate only the non-urgent items with Urgency=50, then create a new Work Entry Point for the arrival of urgent items with Urgency=60.

- Double click on Deliveries, rename it as Deliveries 1, and change the Average inter-arrival time to 5 (12 per hour for non-urgent items)
- Click on the Label Actions button and in the Actions dialogue box click on Add
- In the List of all Labels... dialogue box click on Urgency then OK back to the Actions dialogue box
- From the Label Action options list select Set To, then click on the Value button, set the Fixed value to 50, and OK back to the model
- Hold down the Ctrl key and drag the Deliveries 1 icon to a new location to create a copy of the work entry point named Deliveries 2, with a Route into GrindQ
- Double click on Deliveries 2, change the Average of the Exponential distribution to 20 (3 per hour for the urgent items), in the Label Actions set the Fixed value to 60, and OK back to the model

Edit the GrindQ to prioritise work items using the Urgency label and enable separate results to be collected for the urgent and non-urgent items.

- Double click on the GrindQ icon and in the Storage Bin Properties dialogue box click on Prioritise
- In the List of All Labels ... dialogue box select Urgency and OK back to the Storage Bin Properties dialogue box
- In the Storage Bin Properties dialogue box click on Segregate Results
- In the List of All Labels ... dialogue box select Urgency and OK back to the model
Edit all the work centres to carry the label information down to subsequent queues, edit the latter two queues to prioritise by urgency and segregate results, and edit the Dispatch work exit point so that separate throughput results can be collected.

- In the **Grind 1** work centre, use **Label Actions** to **Add** the label **Urgency** and accept the option **No Change** (in the label value on exit)
- **Repeat** for **Grind 2** and **3**, and **all subsequent work centres**
- In the **PolishQ** queue **Prioritise** and **Segregate Results** by **Urgency**
- **Repeat** for **InspectQ**
- Click on the **Dispatch** icon and in the **Work Complete Properties** dialogue box click on **Segregate Results**, select **Urgency** and **OK** back to the model
- **Run** the model slowly

You should observe work items entering from both Delivery work entry points, but you will not be able to tell if the Urgent items are being given priority in queues.

It is good practice to verify models while developing them, in order to reduce the risk of careless errors getting into models and remaining un-noticed (like a ‘time-bomb’ waiting to create havoc when you eventually run the finished model to make use of the results). This model is a good example of where a fairly simple improvement in the run-time graphical display can make a valuable contribution to verification.

Create a dummy work centre and dummy queue fed from Deliveries 2 to ‘intercept’ work items going from Deliveries 2 to GrindQ. The dummy work centre (with zero duration) will have only one function, namely to change the appearance of urgent items. (You will learn about an alternative label-based method of controlling the image in a later subsection.)

- **Remove the Route Arrow** from Deliveries 2 to GrindQ
- **Create a Storage Area** between Deliveries 2 and GrindQ, rename as **Dummy2Q**, and use the same graphics as the other queues
- **Create a Work Centre** between Dummy2Q and GrindQ, rename as **Dummy 2**, define the **Distribution** as **Fixed** with **Value = 0**, and use the same graphics as the other Work Centres
- **Create Route Arrows** from Deliveries 2 to Dummy2Q, from Dummy2Q to Dummy 2, and from Dummy 2 to GrindQ

The start of your model should now look something like this:
Create an alternative work item icon for the urgent items and use the dummy work centre to change their appearance.

- Use / Graphics / Images / Add from Library, select an alternative image such as BallGreen.bmp in the WorkItems folder, and OK back to the model.
- Double click on Dummy 2, click / Label Action / Add, select Urgency and accept No Change in the Label Actions options, then OK back to the Work Centre Properties dialogue box.
- Click on / Graphics / Work Item's Image on Exit, from the list of Images select Ballgreen, and OK back to the model.
- Run the model slowly to observe the behaviour of urgent items, then at maximum speed to finish the simulation run.

You should fairly soon observe an urgent work item ‘queue-jumping’ in GrindQ, because this is where the longer queues tend to be. You will probably have to wait rather longer before observing this happening in PolishQ and InspectQ.

Compare queuing times and time in the system for urgent and non-urgent items.

- Run a Trial, as before, to obtain means and 95% confidence intervals (for All work items and Segregated by Urgency) for:
  - the Average Queuing Time for GrindQ, PolishQ and InspectQ
  - the Average Time in System
- Summarise your Results below.

<table>
<thead>
<tr>
<th>Results (minutes)</th>
<th>Average</th>
<th>Confidence Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>GrindQ (ave time)</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-urgent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urgent</td>
<td></td>
</tr>
<tr>
<td>PolishQ (ave time)</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-urgent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urgent</td>
<td></td>
</tr>
<tr>
<td>InspectQ (ave time)</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-urgent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urgent</td>
<td></td>
</tr>
<tr>
<td>Time in System</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-urgent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urgent</td>
<td></td>
</tr>
</tbody>
</table>

You should find in each of the queues that the prioritisation results in a shorter queuing time for the urgent items. The advantage will be greatest in GrindQ because these queuing times tend to be longest (so there is more to be gained from ‘jumping the queue’). The shorter times in each of the queues will obviously result in a shorter average time in the system for urgent items.
3.6.2 Using a text label to specify different timing distributions

Labels can also be used to give different categories of work items different timing distributions in work centres. In this case the label is called a Text Label because the values it takes are words not numbers. The name of the text label that is attached to the work items is also used as the name of the corresponding Label-based distribution.

You are now going to assume that the urgent items have a smoother surface than the non-urgent items and consequently tend to have shorter average grinding time. You will assume that the distribution is Normal, with mean 8 and standard deviation 2.

The steps needed are:

(i) create a new text label and attach it to the work items (Gears)
(ii) create a named distribution of grinding times for rougher (non-urgent) gears
(iii) create a named distribution of grinding times for smoother (urgent) gears
(iv) create a label-based distribution of grinding times
   (this is in effect a “conditional” distribution - it enables a Grind work centre to use the appropriate single distribution according to the category of incoming gear)
(v) edit the three grinders to use the new label-based distribution

You will call the new text label Surface Type. The non-urgent raw work items will take the value Rough and the urgent raw work items will take the value Smooth

You will also create named distributions called Rough and Smooth, and a Label-based distribution called Surface Type (a conditional distribution which discriminates between Rough and Smooth items).

Create a new text label and attach it to incoming gears.

- With the model you saved as Gear3f use / Objects / Labels / New
- In the Label Properties dialogue box name the Label as Surface Type, choose the Type of Label as Text, and OK back to the model
- Use / Object / Work Item Types, and in the Work Item Type dialogue box (for work item Gear) click on Add
- Select Surface Type from the List of all Labels... then OK back to the model
Edit the actions at work entry points to assign the Label value Smooth to the incoming items at Deliveries 1, and Rough those at Deliveries 2.

- Double click on the Deliveries 1 icon, click on the Label Actions button, and in the Actions dialogue box click on Add.
- In the List of all Labels... dialogue box select Surface Type then OK back to the Actions dialogue box.
- In the Label Actions options select Set To.
- In the Label Action - Set Text Label box set the Surface Type Label value to Rough, then OK back to the model.
- Repeat the above sequence for the Deliveries 2 work centre to set the Surface Type Label to Smooth.

Create a named distribution of times for rough (non-urgent) incoming gears, and do the same for smooth (urgent) incoming gears.

- Use / Objects / Distributions / New.
- In the New Distribution dialogue box change the name to Rough, select Named distribution and click on Next>>.
- In the Named distribution dialogue box make the distribution Exponential with average 10, then OK back to the Distributions dialogue box.
- Repeat for a distribution Smooth, which is a Normal distribution with average 8 and standard deviation 2, then OK back to the Distributions dialogue box.

Create a label-based distribution that refers to these single distributions, and apply it in the Grind work centres.

- In the Distributions dialogue box click on the New button.
- In the New Distribution dialogue box, select Label Based and click on Next>>.
- In the Label Based Distribution dialogue box select Surface Type from the list of Labels, then OK back to the model.

The text label called Surface Type can have values Rough or Smooth.

So the label-based distribution of the same name can take the form of:
- either the distribution called Rough
- or the distribution called Smooth
depending on the value of the text label.

- Change the distribution in Grind 1, 2 and 3 to Surface Time.
Check the revised model and collect results.

- **Run** the model initially at visual speed, then finish the run at full speed
- **Edit** the **GrindQ** Storage Area and the **Dispatch** Work Exit Point to **Segregate** results by label **Urgency**

Note that only numeric labels can be used for segregation of results.

In this model you have used a text label, Surface Type, and its corresponding label-based distribution to distinguish between the processing times for rough and smooth work items.

If you had not already had a numeric variable, Urgency, with one-to-one correspondence to Surface Type, then you would have needed to create a numeric variable in order to get the segregated results for the rough and smooth work items.

- **Run** a **Trial**, as before, to obtain means and 95% confidence intervals (for **All** work items and **Segregated** by **Urgency**) for
  - the **Average queuing time** for **GrindQ**
  - the **Average Time in System**

- **Summarise** your **Results** below
- **Reset** and **Save** the model (still as **Gear3f**)

<table>
<thead>
<tr>
<th>Results</th>
<th>(minutes)</th>
<th>Average</th>
<th>Confidence Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>GrindQ</td>
<td>All</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urgency = 50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urgency = 60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time in System</td>
<td>All</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urgency = 50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Urgency = 60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compare with the results from the previous version, remembering that

- items with Urgency=50 will also have Surface Type=Rough (having the same distribution as before),
- items with Urgency=60 will also have Surface Type=Smooth (having reduced grinding times).

You should find that:

- as in the previous subsection, on average smooth/urgent items get through the system faster and spend less time queuing for grinding than rough/non-urgent items,
- average waiting times for all items are less than in the previous subsection because the reduction in grinding times for the smooth/urgent gears reduces the overall demand on grinding capacity.
3.6.3 Using labels to control the appearance of work items

Either a **text label** or a **numeric label** can be used to **change** a work item’s **image** after it has been processed in a work centre or work entry point.

### 3.6.3.1 Using text labels

If…  
(i) a work item has a **text label** attached to it with the name **Image**  
(ii) that text label is listed in a work entry point’s Label Actions or a work centre’s Label Actions  
then… (i) Simul8 will look in the list of images defined for that model for an image whose name matches the value of the text label  
(ii) and if a match is found then the work item will be given the appropriate image.

For example

If… the text label **Image** takes the value **BlueBall**  
then… the image of the work item will be changed to **BlueBall** (if that image exists).

You will illustrate this by discriminating graphically between the urgent and non-urgent items. There are convenient images available in the image library (but, if you should want to, you could create your own images or edit an existing image using the Image Editor).

Remove the dummy queue and work centre that you used to change the appearance of urgent work items by a different method in section 3.6.1.

- With the model you saved as **Gear3f**, **erase** the dummy queue **Dummy2Q** and dummy work centre **Dummy 2**, and ensure that the **Route Arrow** from **Deliveries 2** goes to **GrindQ**

Produce images with appropriate names.

- Use **/ Graphics / Images / Add from Library**, select **answer_bad1.bmp** from the **InOutPoints** folder, then **OK** back to the **Images** dialogue box  
- In the **Images** dialogue box select **Answer_bad1** and click on **Properties**  
- In the **Image Editor** change the name to **Red Cross** then **OK** back to the **Images** dialogue box  
- Check that **Red Cross** has been added to the list of Images  
- **Repeat** for the image **answer_good1.bmp** from the same folder, renaming it as **Green Tick**, then **OK** back to the model

You could also use the Image Editor to modify the image before adding them to the list, but this is not necessary here.
Create the text label, attach it to the work items on arrival and assign values to match the image names.

- Use `/Objects / Labels / New` to create a *Text Label* named *Image* then *OK* back to the model
- Use `/Objects / Work Item Types` and with *Gear* as the work item type click on *Add*
- From the *List of all labels*.. select *Image*, then *OK* back to the model
- Double click on *Deliveries 1* and click on *Label Actions*
- Click on the *Add* button and from the *List of all labels*.. select *Image*, then *OK* back to the Actions dialogue box
- From *Label Action* list select *Set to*, in the *Label Actions - Set Text Label* dialogue box set the (text) value to *Red Cross*, then *OK* back to the model
- Repeat for *Deliveries 2*, setting the value of the label to *Green Tick*

Use the enhanced graphics to observe the behaviour of the model.

- **Run** the model initially at visual speed, then finish at maximum speed
- **Reset** and **Save** (still as *Gear3f*)

You should see that most work items are non-urgent (Red Cross) items, from Arrivals 1, and the urgent (Green Tick) items, from Arrivals 2, go to the head of each queue.
### 3.6.3.2 Using numeric labels

If … (i) a work item has a **numeric label** attached to it with a name *beginning* with *Image:*

(ii) and that label is listed in a work entry point’s Label Actions or a work centre’s Label Actions,

then… (i) the value of the numeric label will be attached to the latter part of the label’s name

(ii) and, if an image exists with a name that matches the latter part of the label plus the value, then the work item image will be changed on exit from the work entry point or work centre.

For example…

If… the numeric label *Image:Product* is set to the value 3

then… the image of the work item will be changed to Product3 (if that image exists).

To illustrate this, you will initially make all work items take on a new image in the Wash work centre.

You will then make work items which pass through work centre Polish2 take yet another image.

Produce images with appropriate names.

- With the model you saved as *Gear3f* use / **Graphics** / **Images** / **Add from Library**, select *BOLT_B.BMP* from the **old_images** folder, then **OK** back to the **Images** dialogue box
- In the **Images** dialogue box select *Bolt_b* and click on **Properties**
- In the **Image Editor** change the name to **Product3** then **OK** back to the **Images** dialogue box
- Check the list of images and note that **Product3** has been added to the list of Images, then **OK** back to the model
- **Repeat** for *target.bmp* from the **old_images** folder, renaming it as **Product4**

You can also use the Image Editor to modify images before adding them to the list, but it is not necessary to do so here.
Produce the numeric label, attach the label to the work items and set to appropriate values in work centre Wash.

- Use / Objects / Labels / New to create a Numeric Label named Image:Product then OK back to the model
- Use / Objects / Work Item Types and with Gear as the work item type click on Add
- From the List of all labels.. select Image:Product (one word - no blanks) and OK back to the model
- Double click on the Wash icon and click on Label Actions
- Click on the Add button and from the List of all labels.. select Image:Product and OK back to the Actions dialogue box
- In the Label Action options select Set to, click on the Value button and set to a Fixed value of 3, then OK back to the model
- Run the model initially at visual speed, then finish at maximum speed

You should see that on exit from the Wash work centre all work items take the Product3 image.

Make the image change again for work items that are polished in Polish 2, and check the new graphics.

- Double click on the Polish 2 icon and click on Label Actions
- Click on the Add button and from the List of all labels.. select Image:Product and OK back to the Actions dialogue box
- In the Label Action options select Increment, then OK back to the model

The value of the numeric label is now incremented (increased by 1), so its value is now 4 and Simul8 will look for an image named Product4.

- Run the model initially at visual speed, then finish at maximum speed
- Reset and Save (still as Gear3f)

You should see that work items that pass through Polish 2, on exit, take the Product4 image.

Incrementing the value of a numeric label has many uses.

For example, if some work items are recycled through the system a number of times, then the label can be used to count how many times they are recycled (by incrementing the label in a work centre in the ‘recycling route’ each time).

The numeric label can then be used to segregate the simulation results according to how many times the work items are recycled.

It could also be used to route out the work items to different work exit points according to how many times they are recycled.
3.7 Financial analysis

In queuing systems there is typically a trade-off between service costs and queuing costs. The effective use of resources to improve service/processing capacity, at higher cost, can reduce the cost of queuing. Conversely, applying insufficient resources results in increased queuing costs.

An example of this is a supermarket with many checkouts. Increasing the number of checkouts in operation (the cost of which is reasonably easy to estimate) reduces the risk of customers’ becoming dissatisfied with waiting times for the checkouts and going to shop elsewhere (a real cost, though difficult to quantify). But once there are enough checkouts in operation, staffing too many of them will cost the company more without producing sufficient marginal benefit. The company’s problem is to find a reasonable trade-off.

In this section you will look at cost trade-off in the Gear2 model.

3.7.1 Improving the Grind work centres to reduce costs

First look at the cost of improving the service rate in Grind work centres and the expected reduction in queuing costs. You will start with the model that you saved as Gear2, except that GrindQ will have unlimited capacity so that no deliveries are rejected.

The cost of holding work items in stock is £0.01 per unit per minute in each of the storage areas. You will investigate the effect of a 20% reduction in average processing time in the Grind work centres from 10 to 8 minutes (still exponentially distributed), which is achieved for a 30% increase in cost from £0.50 to £0.65 per unit.

You will then investigate a 40% reduction from 10 to 6 minutes, for a 70% increase in cost from £0.50 to £0.85 per unit.

Assume that all other costs are fixed, the total being £1000 per week, so you do not need to assign any other specific costs in this investigation. The average weekly output is fixed by the delivery rate, since no work items are rejected on arrival, so revenues are ignored and this investigation only looks at costs.

Give the GrindQ storage area unlimited capacity.

- Open the model you saved as Gear2 and save as Gear3g
- Double click on GrindQ, and in the Storage Bin Properties dialogue box change the Capacity to Infinite
Set up the financial information for the current model.

- With the GrindQ dialogue box open, click on the Finance button
  - in the Storage Bin Financial Information dialogue box set the Cost per unit per minute to £0.01
  - OK back to the model
  - repeat for PolishQ and InspectQ

- Double click on Grind 1,
  - click on the Finance button
  - in the Work Centre Financial Information dialogue box set the Usage Cost (Per Unit) to £0.50
  - OK back to the model
  - repeat for Grind 2 and Grind 3

- Use / Finance / Overheads
  - in the Financial Overheads dialogue box set the Fixed Costs to £1000 (over the Results Collection Period, which is 2400 minutes, ie 5 daily 8-hour shifts, or 1 week)
  - OK back to the model

Run the model with current costs.

- Run the model then use / Finance / Income Statement
  - in the Income Statement dialogue box Right-click on Costs (on the text, not on the value) to add this to the Results Summary
  - click on OK

- Run a Trial with 20 Replicates, a Warm Up Period of 480 and a Results Collection Period of 2400, to obtain means and 95% confidence intervals for
  - the total weekly Costs on Income Statement
  - the Queuing Time Average for All items in GrindQ
  - the Queuing Time Average for All items in PolishQ
  - the Queuing Time Average for All items in InspectQ

- Summarise your Results below

Summary of results:
Modify the model to assess the cost implications of shorter grinding times.

- Use / Objects / Distributions / GrindDist to change the Average to 8
- Double click on Grind 1, click on Finance to change the Usage Cost (Per Unit) to £0.65, then OK back to the model
- Repeat for Grind 2 and Grind 3
- Run a Trial, as before, to obtain means and 95% confidence intervals for
  - the total weekly Costs on Income Statement
  - the Queuing Time Average for All items in GrindQ
  - the Queuing Time Average for All items in PolishQ
  - the Queuing Time Average for All items in InspectQ

- Summarise your Results below, and compare with the previous results

You should find that there is an effective trade-off, with a worthwhile reduction in total costs as a result of reduced queues in GrindQ.

Summary of results:

Look at a further reduction in grinding times.

- Change the GrindDist distribution Average to 6
- Change the Grind 1, 2 and 3, Usage Cost (Per Unit) to £0.85
- Run a Trial, as before, to obtain means and 95% confidence intervals for
  - the total weekly Costs on Income Statement
  - the Queuing Time Average for All items in GrindQ
  - the Queuing Time Average for All items in PolishQ
  - the Queuing Time Average for All items in InspectQ

- Summarise your Results below, and and compare all three sets of results
- Reset and Save the model (still as Gear3g)

You should find that the higher cost of better performance in the Grind work centres is not justified.

Summary of results:
3.7.2 Improving the Grind work centres to increase profit

3.7.2.1 A provisional model

Start with the same properties as model Gear2, including a storage capacity of 25 in GrindQ. Assign a value of £5 per unit to the delivered raw gears and a value £10 per unit to the finished gears leaving the system. Initially assume that if a delivered work item is rejected it is ‘thrown away’, while still incurring the £5 unit cost.

Also assume, as before, that the cost of holding work items is £0.01 per unit per minute in each storage area, and that all other costs, excluding Grind work centres processing costs (£0.50 per unit per minute), total £1000 per week.

You will investigate the net effect on value of items per week of a 20% reduction in average processing time in the Grind work centres for a 30% increase in cost per unit. Then you will investigate a 40% reduction in average processing time, for a 70% increase in cost per unit.

Set up the initial values, including unit costs of delivered items and revenue per finished Unit.

- With the model you saved as Gear3g set the Capacity of GrindQ back to 25
- Set the Average of the GrindDist distribution back to 10
- Set the Usage Cost (Per Unit) in each Grind work centre back to £0.50
- Confirm that the Cost per item per minute in each queue is £0.01
- Confirm that the Fixed Costs in Financial Overheads are £1000
- Double click on Deliveries, click on the Finance button, set the Cost (Per Unit) to £5.00, and OK back to the model

This is the unit value of delivered items.

- Double click on Dispatch, click on the Finance button, set the Revenue (Per Unit) to £10.00, and OK back to the model

This is the unit value of finished items.
Run the model with current costs.

- Run the model then use / Finance / Income Statement to add Revenue and Profit to the Results Summary
- Run a Trial, as before, to obtain means and 95% confidence intervals for
  - the total weekly Costs in Income Statement
  - the total weekly Revenue in Income Statement
  - the total weekly Profit in Income Statement
  - the Queuing Time Average for All items in GrindQ
  - the Queuing Time Average for All items in PolishQ
  - the Queuing Time Average for All items in InspectQ
  - the Number of work items lost in Deliveries
- Summarise your Results below

Summary of results:

Modify the model to assess the cost implications of shorter grinding times.

- In GrindDist change the Average to 8
- In Grind 1, 2 and 3 change the Usage Cost (Per Unit) to £0.65
- Run a Trial to collect results as before
- Summarise your Results below, and compare with the previous results

Summary of results:
Look at a further reduction in grinding times.

- Change the **GrindDist** distribution **Average** to **6**
- In **Grind 1, 2 and 3** change the **Usage Cost (Per Unit)** to **£0.85**
- Run a **Trial** to collect results, as before
- Summarise your **Results** below, and compare all three sets of results
- **Reset** and **Save** the model (still as **Gear3g**)

### Summary of results:

<table>
<thead>
<tr>
<th>Gear3g</th>
<th>Gear3g</th>
<th>Gear3g</th>
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</thead>
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</tbody>
</table>

#### 3.7.2.2 An improved model

In a production system such as this it is unlikely that a work item rejected because of limited capacity in GrindQ would be totally lost. It is more likely that it would be returned to source for later delivery, and that the cost of doing so would be some fraction of the value.

Assume that the cost is £0.50 per rejected item. You can model this behaviour by creating a work exit point (in which the unit value is reduced to £4.50 and with a route from Deliveries) to capture the rejected items when the GrindQ storage area is full. The routing out from Deliveries will be prioritised to send items to GrindQ if possible.

Repeat the previous analysis under this improved assumption. The start of your model will be revised to look something like this:
Modify the model and set up the initial values.

- With the model you saved as Gear3g create a Work Exit Point named Returns Bin and with the same Graphics as Dispatch, located below Deliveries.
- Create a Route Arrow from Deliveries to Returns Bin.
- In Deliveries set the Routing Out Discipline to Priority with GrindQ above Returns Bin.

Now the model will not reject any incoming work items. Instead, the work items will go into GrindQ if there is room, but into the Returns Bin if the storage area is full.

- Double click on Returns Bin, click on the Finance button, set the Revenue (Per Unit) to £4.50, and OK back to the model.

The £0.50 cost in returning a rejected work item (instead of writing off the whole £5.00 value) is modelled as a reduction in value from £5.00 at the Deliveries work entry point to £4.50 at the Returns Bin work exit point.

Run the model with current costs.

- Change the GrindDist distribution Average to 10.
- Change the Grind 1, 2 & 3 Usage Cost (Per Unit) to £0.50.
- Run the model then:
  - double click on Deliveries then on Results to remove Number of work items lost from the Results Summary.
  - double click on Returns Bin then on Results to add Work Completed (ie rejected items returned) to the Results Summary.
- Run a Trial, as before, to obtain means and 95% confidence intervals for:
  - the total weekly Costs in Income Statement.
  - the total weekly Revenue in Income Statement.
  - the total weekly Profit in Income Statement.
  - the Queuing Time Average for All items in GrindQ.
  - the Queuing Time Average for All items in PolishQ.
  - the Queuing Time Average for All items in InspectQ.
  - the Work Completed in Returns Bin.
- Summarise your Results below.

Summary of results:
Modify the model to assess the cost implications of shorter grinding times.

- Change the **GrindDist** distribution **Average** to **8**
- In **Grind 1, 2 & 3** change the **Usage Cost (Per Unit)** to **£0.65**
- Run a **Trial** to collect results as before and summarise your **Results** below

**Summary of results:**

Look at a further reduction in grinding times.

- Change the **GrindDist** distribution **Average** to **6**
- In **Grind 1, 2 & 3** change the **Usage Cost (Per Unit)** to **£0.85**
- Run a **Trial** to collect results as before and summarise your **Results** below

**Summary of results:**

Inspect all results for the provisional and the revised model. In both models you should find that the first increase in Grind costs and corresponding reduction in processing times prevent rejection of work items at Deliveries, giving a greater profit. Once there are no rejected items, there is no point in further improvement in Grind times because the increased processing costs will be greater than the overall reduction of storage area costs.

Compare each set of revised model results with the corresponding provisional model results. The only difference between the two models is the value assigned to rejected items in Deliveries. So, provided you used the same random numbers, you should get the same results when there are no rejected items in each model (with each improvement in the Grind work centres). At current costs the results should also be the same for each model except for the slightly higher total revenue from the returned (instead of rejected) work items in the revised model, and a corresponding small increase in profit.
3.8 Visual Logic

You have seen how to put controls into your simulation models using the menu system, the toolbar buttons and the dialogue boxes. An alternative approach is to put controls into a model by writing code in the programming language Visual Basic, and many experienced users regularly take advantage of this.

Of course, ‘novice’ simulation analysts would not want to write computer code (unless they were experienced computer programmers, possibly), because it would entail learning the programming language. There is a Simul8 ‘wizard’ called Visual Logic that helps users to write the commands correctly, once they know they want to do. But even using Visual Logic to put in the controls tends to be more difficult for most users of Simul8 than using the menu system, the toolbar buttons and the dialogue boxes.

So can Visual Logic still have a role for anyone other than the more experienced users of Simul8? The answer is ‘yes’, because Visual Logic can be used to put in controls that cannot be created in the conventional way. A listing of all Visual Logic commands, with explanations and where they can be applied in a simulation model, can be found in the Help menu under Visual Logic.

The following two examples present you with a brief introduction to Visual Logic. They are both based on the model in Gear2, which looked something like this:
3.8.1 Prioritising work centres

Prioritising the routing of work items can be done fairly simply without Visual Logic. For example:
- Section 3.4.3 illustrates the use of priority routing into a work centre from different queues.
- Section 3.6.1 illustrates the use of numeric labels to prioritise access to a queue.

However, Visual Logic gives greater flexibility, allowing the analyst to simulate more complex systems.

In this first example you will illustrate the use of Visual Logic to prioritise the Polish work centres so that work items only go to work centre Polish 2 if Polish 1 is busier than Polish 2.

You will need to modify the model by putting in separate queues for the two Polish work centres. This part of the model will then look similar to the one shown here.

Then you will be able to create Visual Logic commands to control the routing from the Wash work centre.

Insert the new storage area for Polish 2 and put in the appropriate routes.

- Open the file called Gear2 and Save as Gear3h
- Rename PolishQ as PolishQ 1, use Ctrl/Drag to copy PolishQ 1, creating a new storage area named PolishQ 2
- Use Shift/Drag to remove the Routing Arrows
  - from PolishQ 1 to Polish 2
  - and from PolishQ 2 to Polish 1
- Double click on the Wash icon, click on Routing Out, confirm that the default Routing Out Discipline is Circulate and OK back to the model
- Run the model initially at visual speed to observe the behaviour of this part of the model, then finish the run at full speed
- Run a Trial with 20 Replicates, a Warm Up Period of 480, and a Results Collection Period of 2400, to obtain means and 95% confidence intervals for Percentage of Time Working for Polish 1 & 2
- Summarise your Results here

You should observe that the two work centres have approximately the same level of utilisation, any difference being caused by variation between individual simulated polishing times.
Before using Visual Logic to create the required routing logic (which cannot be done through the menus and dialogue boxes in the usual way) try implementing a simpler priority rule in which Polish 1 is always chosen in preference to Polish 2. This will mean that work items are only sent to Polish 2 when Polish 1 reaches its maximum capacity.

Implement this simpler priority rule.

- Double click on the Wash icon, in the Work Centre Properties dialogue box click on Routing Out, then in the Discipline options select Priority
- Try changing the order of the routing list by selecting one of PolishQ 1 or PolishQ 2 and using the control buttons, but ensure that you finish up with
  - PolishQ 1 as the 1st priority route
  - PolishQ 2 as the 2nd priority route
- OK back to the model

- Select the PolishQ 1 icon then click on the Make time graph of selected objects button, reduce the height and stretch the horizontal axis
- Repeat for PolishQ 2
- Run the model initially at visual speed to observe the behaviour of this part of the model, then finish the run at full speed
- Run a Trial, as before, to obtain means and 95% confidence intervals for Percentage of Time Working for Polish 1 & 2

- Summarise your Results here
- Reset and Save (still as Gear3h)

You should observe that after the warm up period there are always work items in the PolishQ 2 storage area, so Polish 1 is fully utilised. The utilisation of Polish 2 is low because PolishQ 2 can only receive a work item if one arrives when the PolishQ 2 storage area is full to capacity.

You will now prepare for using Visual Logic to set up the new routing logic, by making the routing out from Wash depend on a Label which is attached to work items in the Wash work centre. Before including the more complex rule in Visual Logic, this Label will always send work items to Polish 1.

Create the label and attach it to the work items.

- Use / Objects / Labels to create a New Label
  - name the Label as Route for Polishing
  - ensure the Type is Number and OK back to the model
- Use / Objects / Work Item Types
  - in the Work Item Types dialogue box, with Gear selected click on Add
  - in the List of All Labels... select Route for Polishing
  - OK back to the model
Use the Label to route all the work items to Polish 1.

- Double click on the **Wash** icon and in the **Work Centre Properties** dialogue box click on **Label Actions**
  - in the **Actions** dialogue box click on **Add**
  - from the **List of all Labels** dialogue box click on **Route for Polishing** and **OK** back to the **Actions** dialogue box
  - in the **Label Action** options list select **Set to**
  - in the **Label Value** dialogue box ensure that the **Fixed Value** is set to 1 (so that every work items takes route number 1)
  - **OK** back to the **Work Centre Properties** dialogue box

- In the **Work Centre Properties** dialogue box click on **Routing Out**
  - in the **Discipline** options select **Label** and click on **Detail**
  - in the **List of All Labels** dialogue box click on **Route for Polishing** and **OK** back to the **Routing Out From** dialogue box
  - try changing the order of the routing list by selecting one of **PolishQ 1** or **Polish 2** and using the **control buttons**, but ensure that you finish up with **PolishQ 1** as route 1, and **PolishQ 2** as route 2
  - **OK** back to the model

- **Run** the model initially at visual speed to observe the behaviour of this part of the model, then finish the run at full speed

- **Run a** **Trial**, as before, to obtain means and 95% confidence intervals for **Percentage of Time Working** for **Polish 1 & 2**

- **Summarise your** **Results** here

You can now begin to set up the routing logic, using these Visual Logic commands for Label Actions in Wash (ie to control the value of the label, which controls the routing out from Wash).

The logic is:

- the Label value is initially set to 1 (which defines the route as going to Polish 1)
- but the Label is changed to 2 (which defines the route as going to Polish 2) if there are more work items queuing for Polish 1 than for Polish 2.
The first step is to use Visual Logic to set the Wash work centre Route Out value to 1.

- Double click on the Wash icon and click on Labels Actions
  - in the Actions dialogue box click on the If .. Visual Logic button
  - when the Visual Logic window appears press your Insert key (or Right-click on your mouse)
  - from the pop-up menu select Set ... = ...
- In the Set Value dialogue box
  - double click in the Information (left hand side) ??? field
  - in the Formula Editor dialogue box, under Select a type of list choose Object
  - in the left hand Objects List double click on Route for Polishing
  - OK back to the Set Value window

- In the Set Value window
  - double click in Calculation (right hand side) ??? field
  - in the Formula Editor dialogue box, keep the type of list as Information
  - type directly into the ?? box the value 1
  - OK back to the Visual Logic window

The commands in the Visual Logic window will look like this:

All work items will be routed to PolishQ 1, since that is route number 1 in the Wash routing out list.

- Close the Visual Logic window and OK back to the model
- Run the model initially at visual speed to observe the behaviour of this part of the model, then finish the run at full speed
- Run a Trial, as before, to obtain means and 95% confidence intervals for Percentage of Time Working for Polish 1 & 2

- Summarise your Results here

<table>
<thead>
<tr>
<th>Polish 1:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polish 2:</td>
</tr>
</tbody>
</table>

You should again observe that only Polish 1 is utilised.

Next you need to include the condition to re-route to PolishQ 2 if there are fewer in that queue than in PolishQ 1.

- Double click on the Wash icon and click on Labels Actions window
  - in the Actions dialogue box click on the If .. Visual Logic button
  - in the Visual Logic window, with the Set Route for Polishing = 1 line selected press your Insert key (or Right-click on your mouse)
  - from the pop-up menu select If ... (Else / While etc)
- In the Conditional Block Editor dialogue box
  - ensure the Type is If
  - double click in the Upper ??? input field
In the **Formula Editor** dialogue box, under **Select type of list** 
choose **Object**  
- in the left hand **Objects List** double click on **PolishQ 1** (DON’T click OK)  
- then in the right hand **Properties List** double-click on **Count Contents**  
  (ie number in the queue)  
- **OK** back to the **Conditional Block Editor** dialogue box

To **change** the condition from **equals**  
- click on the downward **Selector Arrow**  
- select the **>** (is greater than) relationship

Double click in the **Lower ???** field  
- in the **Formula Editor** dialogue box, under **Select type of list** 
choose **Object**  
- then in the left hand **Object** list double click on **PolishQ 2**  
- in the **Properties List** double-click on **Count Contents**  
- **OK** back to the **Visual Logic** window

The commands in the Visual Logic window should look like this:

Finally you need to define what happens when the number of work items in PolishQ 1 is more than in PolishQ 2.

Double click on the **Insert logic here to use "If" condition is true** line  
(which has the same effect as pressing the Insert key)  
and from the pop-up menu select **Set ... = ...**

In the **Set Value** window  
- double click in the **Information** (left hand side) ??? field  
- in the **Formula Editor** dialogue box, under **Select type of list** 
choose **Object**  
- in the **Objects List** double click on **Route for Polishing**  
- **OK** back to the **Set Value** window

In the **Set Value** window  
- double click in the **Calculation** (right hand side) ??? field  
- in the **Formula Editor** dialogue box, keep the **type of list** as **Information**  
- **type directly** into the ??? box the value **2**  
- **OK** back to the **Visual Logic** window

The commands in the Visual Logic window should look like this:

When the number of work items in PolishQ 1 is more than in PolishQ 2 the route will be changed to send work items to PolishQ 2.
Now check the modified simulation.

- Close the Visual Logic window and OK back to the model
- Open the Time Graph for PolishQ 2 as well as PolishQ 1, reduce the height of each and stretch both to the same width
- Run the model initially at visual speed to observe the behaviour of this part of the model, then finish the run at full speed
- Run a Trial, as before, to obtain means and 95% confidence intervals for Percentage of Time Working for Polish 1 & 2
- Summarise your Results here

<table>
<thead>
<tr>
<th>Polish 1:</th>
<th>Polish 2:</th>
</tr>
</thead>
</table>

You should now see that polishing is done in both work centres but more is done in Polish 1 than in Polish 2. There will also be more queuing in PolishQ 1 than PolishQ 2.

- Reset to model, close the Time Graph windows and Save (still as Gear3h)

### 3.8.2 Using an extra grinding machine when there is high demand

In this second example, the grinding will be done in work centres Grind 1 and Grind 2, but Grind 3 will be used if there are too many raw gears awaiting grinding. This is like the system in supermarkets when extra tills are opened up as soon queues are seen to be getting too long.

Incoming gears arrive randomly at an average rate of 15 per hour. Initially, you will leave out the work centre Grind 3. You will also increase the average work rate of work centres Grind 1 and Grind 2 to 8 per hour each, so that their combined capacity is just greater than the average arrival rate.

However, it will not be sufficient to avoid a lot of raw gear mouldings waiting for grinding during the periods when the processing rate is not matched to the arrivals. This will occur often because the combined processing capacity is not much more than the arrival rate and there is a lot of random behaviour in the arrivals and the processing.

You will then modify the model to allow Grind 3 (with the same work rate) to be used when at least 10 raw gear mouldings are waiting in the Grind storage area. Assume, however, that the storage area for Grind 3 is restricted, so raw gear moulding will only be diverted if there are less than 5 in this storage area.
When you have modified the first part of the model it should look something like this.

As in the previous model, you are going to use Visual Logic to control routing using the Label Routing Out option. In the previous model you found out how to access Visual Logic via the Label dialogue box. However, in this model you will find out how to access Visual Logic via the Routing Out dialogue box.

A work entry point such as Deliveries has the same routing out options as a work centre, but it does not have access to Visual Logic in the Routing Out dialogue box, as a work centre does. So a dummy work centre, Choose Route, is inserted, and it is in the Routing Out dialogue box of this dummy work centre that Visual Logic will be used.

The dummy queue before Choose Routes is not essential, but is inserted because it is good practice to put a queue before every work centre unless you know that there is a definite reason not to (to avoid possible conflict between an upstream routing out rule and a downstream routing in rule).

Modify the Grind work centres.

- With the model you saved as Gear3h, use / Objects / Distributions, select GrindDist, and click on Properties
- In the Named Distribution dialogue box keep the Distribution as Exponential, but change the Average time to 7.5 minutes (average work rate 8 per hour in each work station) and OK back to the model
- Remove the routing link from GrindQ to Grind 3
- Run the model initially at visual speed to observe the behaviour of this part of the model, then finish the run at full speed
- Open the Time Chart for the GrindQ to observe the queue length over time, then run the model for a few more replicates with different random number streams
- Run a Trial, as before, to obtain means and 95% confidence intervals for Percentage of Time Working for Grind 1 & 2
- Summarise your Results here

| Grind 1: |
| Grind 2: |
You will have seen that the queue length sometimes reaches 25 so that incoming gears are rejected. To avoid this happening, you will put Grind 3 back into the system and allow it to operate when there are at least 10 items in the storage area GrindQ.

Create a separate storage area for Grind 3, and a dummy work centre to control the routing using a numeric Label (preceded by a dummy queue). You may need to adjust the positions of some of the existing icons.

- **Reset** the model and display the Route Arrows
- **Remove** the link from Deliveries and GrindQ
- Use the Create Storage Area tool to place a work centre between Deliveries and GrindQ
  - change the Name to DummyQ
  - set the Graphics to display the Title, Count and Queue
- Use the Create Work Centre tool to place a work centre between DummyQ and GrindQ
  - change the Name to Choose Route
  - change the Timing to a Fixed value of 0
  - set the Graphics to display the Image, Title and Count
- Use the Create Work Centre tool to place a work centre between Deliveries and GrindQ
  - change the Name to Choose Route
  - set the Timing to a Fixed value of 0
  - set the Graphics to display the Image, Title and Count
- Use the Create Storage Area tool to place a queue between the Choose Route dummy work centre and Grind 3
  - change the Name to GrindQ 3
  - set the Capacity to 10
  - set the Graphics to display Queue, Count and Title
- Insert the Routing links
  - from Deliveries to Choose Route
  - from Choose Route to GrindQ
  - from Choose Route to GrindQ 3
  - from GrindQ 3 to Grind 3
In order to allow the third Grind centre to be used when the queue for the other two gets too long, you can use Visual Logic to create the following rule for controlling the routing from the Choose Route dummy work centre:

Create a label to control the routing and assign it to the work items.

- Use / Objects / Labels / New to create a label named Route for Grinding for which the Type is Number.
- Use / Objects / Work Items Types to Add the label Route for Grinding to the Gear work item type.

Set up the new routing out discipline, then create the first line of the Visual Logic rule.

- Select the dummy work centre Choose Route and click on Routing Out.
- In the Routing Out From dialogue box set the Discipline to Label, using the label Route for Grinding with:
  - GrindQ as the 1st route out.
  - GrindQ 3 as the 2nd route out.
- In the Routing Out From dialogue box, if the Visual Logic options are not displayed then click on More >>.
- Click on IF... …Before exit.
- When the Visual Logic window appears press your Insert key and from the pop-up menu select Set ... = ...
- In the Set Value window:
  - in the (left hand) Information field enter Route for Grinding.
  - in the (right hand) Calculation field enter the value 1.
  - OK back to the Visual Logic Editor.
Create the first condition.

- Press Insert and from the pop-up menu select IF ... (Else / While etc)
- In the Conditional Block Editor dialogue box
  - ensure the Type is If
  - in the Upper ??? field enter GrindQ.Count Contents
  - change the condition to >=
  - in the Lower ??? field enter the value 10
  - OK back to the Visual Logic Editor

Create the second condition.

- Press Insert and from the pop-up menu select IF ... (Else / While etc)
- In the Conditional Block Editor dialogue box
  - ensure the Type is If
  - in the Upper ??? field enter GrindQ 3.Count Contents
  - change the condition to <
  - in the Lower ??? field enter the value 5
  - OK back to the Visual Logic Editor
Define the action to be taken if both conditions are satisfied.

- Press **Insert** and from the pop-up menu select **Set ... = ...**
- In the **Set Value** window
  - in the (left hand) **Information** field enter **Route for Grinding**
  - in the (right hand) **Calculation** field enter the value **2**
- **OK** back to the model
- **Run** the model initially at visual speed to observe the behaviour of this part of the model, then finish the run at full speed
- **Observe the** **Time Chart** for the **GrindQ**, then run the model for a few more replicates with different random number streams

The time graph should show that this third grind centre has enabled the system to cope with the arrivals without allowing such big queues building up.

- **Run a** **Trial**, as before, to obtain means and 95% confidence intervals for **Percentage of Time Working** for **Grind 1, 2 & 3**

- **Summarise your** **Results** here

<table>
<thead>
<tr>
<th>Grind 1:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grind 2:</td>
</tr>
<tr>
<td>Grind 3:</td>
</tr>
</tbody>
</table>

You should find that the utilisation of Grind 3 is less than that of the other two.