Simulation Models for Manufacturing Systems

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Manufacturing System Simulation Models

- Simulation Models as any other model aim to achieve a platform for analysis and evaluation of real systems.
- Simulation models tend to be ideal when dealing with
  - Complex systems
  - Dynamic, time-variant behaviour of systems
  - Random behaviour/characteristics of systems
  - Complex control strategies that depend on numerous factors
  - The need to map data gathered from the real system into the model
Manufacturing System Simulation Models

- Simulation is a procedure for experimentation with a model
  - Proper experimental design is required
    - What are the performance parameters we are after?
    - What are the conditions/decision variables we want to analyse to determine the effect on the performance parameters?
    - What are the constraints/characteristics that bound our simulated system?
  - Results are typically statistical data
    - Average values
    - Distributions
    - Variances

Components in a Manufacturing System Simulation Model

- Simulation Languages
  - A special purpose computer language
    - Includes constructs for building models, performing experimental analysis, and recording results
      - General Purpose Languages used for simulation (C/C++, VISUAL BASIC)
      - Specifically developed languages (SIMAN/ SIMULA)
Components in a Manufacturing System Simulation Model

- Simulation Package / System
  - Integrates a simulation language with other supporting software tools
    - Graphical model editors
    - Statistical analysis tools
    - Animation tools
    - Report and graph generators
  - Example – ARENA, EXTEND, SIMPLE++
Simulation Model Examples

Simulation Model Examples
Simulation Model Examples

Simulation Model Examples

<table>
<thead>
<tr>
<th>Category</th>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency Room</td>
<td></td>
</tr>
</tbody>
</table>

Key Performance Indicators

<table>
<thead>
<tr>
<th>Category</th>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Entities</td>
<td></td>
</tr>
<tr>
<td>Arrived</td>
<td>760</td>
</tr>
<tr>
<td>Other Cells</td>
<td>1</td>
</tr>
<tr>
<td>Transfer Cells</td>
<td>560</td>
</tr>
<tr>
<td>WIP Input Cells</td>
<td>2,005</td>
</tr>
<tr>
<td>WIP Cells</td>
<td>2,001</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$6,997</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>All Resources</th>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Every Cell</td>
<td>1.01</td>
</tr>
<tr>
<td>Idle</td>
<td>1.01</td>
</tr>
<tr>
<td>Inactive</td>
<td>0.00</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$1.00</td>
</tr>
</tbody>
</table>

Emergency Room: Category Overview

Simulation Model Examples
Elements of a Manufacturing System Simulation Model

- Entities
- Resources
- Queues
- Events
- Performance Measures

Entities

- Represent the elements that move around through the system model
- Changes status while transitioning through the model
- They influence and are influenced by other entities as well as the system state

Entity Examples
- Parts
- Batches
- Orders
- Tags
Elements of a Manufacturing System Simulation Model

- **Entities**
  
  Entities are the *dynamic elements* of the model

![Diagram showing entity creation and disposal](image)

- **Entity Creation Examples**:
  - Part arrives on the line
  - Batch is released for production
  - Order for Production

- **Entity Disposal Examples**:
  - Finished Product leaves line
  - Batch is shipped

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Attributes of Entities

- Time entity enters system
- Time entity starts being processed at a station
- Part Code
- Due Date, etc.
Elements of a Manufacturing System Simulation Model

- Entities

System Model as an entity
- Attributes (Global Attributes):
  - Simulation Time
  - Parts in System
  - Parts waiting in Queue
  - Mean throughput time, etc..

- Resources

Handle entities by *servicing* the entities
Elements of a Manufacturing System Simulation Model

- **Resources**

  - Entities ‘compete’ to be serviced by the resource.
  - Resources consist of one or more **servers**
    - **multiple servicing** of entities

  ![Diagram of Resources](image)

  - Operators at a processing station
  - Material Carrying Devices in a Material Handling System

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**Entity:**
- A unit that is processed or handled by a server.

**Server:**
- A unit of a resource that is responsible for processing or handling entities.
Elements of a Manufacturing System Simulation Model

- **Resources**

  Entities waiting to be serviced by Resource

  A server (resource unit) can service a single unit at any instance in time.
  - Entity **seizes** a server to be serviced
  - Entity is **serviced** by server
  - Entity **releases** server following service completion

- **Resources**

  - Attributes of a Resource – Current State of servers
    - busy
    - idle
    - blocked
    - starved
    - Broken/Failed etc..
Elements of a Manufacturing System Simulation Model

- Queues
  - Entities that cannot proceed to the next operation
  - Example of Queues
    - Buffer Storage ahead of a station
    - Orders to be processed
    - Waiting Servicing for machines

- Attributes of Queues
  - Capacity Available
  - Handling of entities in queue
    - FIFO
    - LIFO etc..

Elements of a Manufacturing System Simulation Model

- Events
  - Time Instance
  - State Change
  - Event A: Entity Arrives (Created)
  - Event B: Entity Enters Queue
  - Event C: Entity Seizes Resource and starts service
Elements of a Manufacturing System Simulation Model

- Events

**Typical Events**
- Arrival of a Part in the system
- Commencement of servicing at a resource server
- Finalisation of servicing at a resource server
- Departure of a Part from the system

**Event Attributes**
- Time of Event occurrence
- Event Identifier (type of event)
- Future events to be scheduled by event

**Event List/ Calendar**
- $T_A$ Event A
- $T_B$ Event B
- $T_C$ Event C...

**Event Scheduling**

**Time Between Events**
- Deterministic (ex. 1.2 mins)
- Random (ex. Unif. Dist. Between 1.0 and 1.4 mins)
Elements of a Manufacturing System Simulation Model

- **Performance Measures**
  - Parameters used to interpret behaviour of simulation model

<table>
<thead>
<tr>
<th>Time Persistent</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurable at any simulation time</td>
<td>Measurable at event times</td>
</tr>
</tbody>
</table>

- **Time Persistent**
  - Queue Lengths
  - State of Resource
  - Work in Process
  - No of Parts Produced

- **Observed**
  - Part Processing Time
  - Time Spent in Queue
  - Time Resource is idle

Statistical Accumulators
Elements of a Manufacturing System Simulation Model

- General Statistical Accumulators Used
  - Number of parts produced
  - Total waiting time in queue
  - Number of parts passing through queue
  - Longest time spent in queue
  - Longest time spent in system

- Area under the queue-length curve
- Area under the server-busy function
- Makespan
- Percentage Failures
- Congestion
Elements of a Manufacturing System Simulation Model

- Other Simulation Parameters
  - Simulation Clock
  - Initialisation / Termination Mode

Understanding Discrete Event Simulation

- An Example
  - Processing of Blank Parts at a Drilling Station

Part Arrives

If Station is Idle

Part Starts Servicing Immediately

If Station is Busy

Part Enters a First-In-First-Out Queue
Understanding Discrete Event Simulation

- Drill Example

<table>
<thead>
<tr>
<th>Entities</th>
<th>Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource</td>
<td>Drill Press (Single server)</td>
</tr>
</tbody>
</table>
| Events     | 1. Part Arrives  
2. Part Starts Service  
3. Part Completes Service |

Understanding Discrete Event Simulation

- Drill Example – Event Based Model

<table>
<thead>
<tr>
<th>Event</th>
<th>State Change</th>
</tr>
</thead>
</table>
| 1. Part Arrives            | No. of Parts in System Increases  
No. of Parts in Queue Increases |
| 2. Part Starts Service     | No. of Parts in Queue Decreases  
Drilling Machine becomes Busy |
| 3. Part Completes Service  | No. of Parts in System Decreases  
Drilling Machine becomes Idle |
Understanding Discrete Event Simulation

Drill Example – Event Based Model

- Event Interaction: Using an Event Graph

Event Trigger: Inter-arrival time
Event Action: Place part in FIFO queue
Event Scheduling: Part Arrives
Part Starts Service
Part Completes Service

Inter arrival time
(if machine idle)
Part Arrives
Part Starts Service
Service time
Part Completes Service
(if station queue not empty)

Event Trigger: Service time
Event Action: Part Releases Resource
Event Scheduling: Part Starts Service (Conditional)

Understanding Discrete Event Simulation

Drill Example

Event Based Model

- Models the system through the Definition of Events, the subsequent state changes and the Event Interactions
Understanding Discrete Event Simulation

- Drill Example

**Process Based Model**

- Alternative Viewpoint – Model the system as an **Ordered Sequence of Events followed by an Entity**
- Process Conditions can Modify the sequence of Events followed by the Entity
- Facilitates representation of Manufacturing Processes

*NOTE: The Model is Still Driven by EVENTS*

**Drill Example – Process Based Model**

- Process Steps
  - Wait Till Part's Turn to be serviced
  - Wait for Servicing Time
  - Part Arrives
    - Event: Part Arrives
  - Part Enters Queue
    - Event: Start Service
  - Part Is Serviced
    - Event: Complete Service
  - Part Leaves System
Understanding Discrete Event Simulation

Drill Example – Running the Simulation

2 Events
- Part Arrival
- Part Departure

2 Resource States
- IDLE
- BUSY

Event Routine – Part Arrival

Start
Add Part to queue
Yes
Is Drill Busy?
No
Seize Drill and make Drill State = Busy
Schedule Part Departure Event

End
Understanding Discrete Event Simulation

Drill Example – Running the Simulation

Event Routine – Part Departure

Start

Dispose of Finished Part

Make Drill Press = Idle

Yes

Is Queue Empty?

No

1st Part in Queue seizes Drill
Queue length reduced

Schedule Part Departure Event

End

Drill Example – Running the Simulation

Simulation Data

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Arrival Time</th>
<th>Inter-arrival Time</th>
<th>Service Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>1.73</td>
<td>2.90</td>
</tr>
<tr>
<td>2</td>
<td>1.73</td>
<td>1.35</td>
<td>1.76</td>
</tr>
<tr>
<td>3</td>
<td>3.08</td>
<td>0.71</td>
<td>3.39</td>
</tr>
<tr>
<td>4</td>
<td>3.79</td>
<td>0.62</td>
<td>4.52</td>
</tr>
<tr>
<td>5</td>
<td>4.41</td>
<td>14.28</td>
<td>4.46</td>
</tr>
<tr>
<td>6</td>
<td>18.69</td>
<td>0.70</td>
<td>4.36</td>
</tr>
<tr>
<td>7</td>
<td>19.39</td>
<td>15.52</td>
<td>2.07</td>
</tr>
<tr>
<td>8</td>
<td>34.91</td>
<td>3.15</td>
<td>3.36</td>
</tr>
<tr>
<td>9</td>
<td>38.06</td>
<td>1.76</td>
<td>2.37</td>
</tr>
<tr>
<td>10</td>
<td>39.82</td>
<td>1.00</td>
<td>5.38</td>
</tr>
<tr>
<td>11</td>
<td>40.82</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Understanding Discrete Event Simulation

Drill Example – Running the Simulation

Initialisation - Time 0.0

Event: Part 1 Arrival - Time 0.0
Understanding Discrete Event Simulation

- Drill Example – Running the Simulation

**Event : Part 2 Arrival - Time 1.73**

<table>
<thead>
<tr>
<th>System State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Status</td>
</tr>
<tr>
<td>Number in queue</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simulation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.73</td>
</tr>
</tbody>
</table>

**Event List**

- Arr 1.73
- Dep 2.90

**Times of arrival**

- 1.73

---

**Event : Part 1 Departure - Time 2.90**

<table>
<thead>
<tr>
<th>System State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Status</td>
</tr>
<tr>
<td>Number in queue</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simulation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.90</td>
</tr>
</tbody>
</table>

**Event List**

- Dep 2.90
- Dep 3.666
### Understanding Discrete Event Simulation

- **Drill Example – Running the Simulation**

#### Event: Part 3 Arrival - Time 3.08

<table>
<thead>
<tr>
<th>System State</th>
<th>Simulation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Status</td>
<td>3.08</td>
</tr>
<tr>
<td>Number in queue</td>
<td>1</td>
</tr>
</tbody>
</table>

**Event List**

- **Arr. 3.08**
- **Dep. 4.66**

#### Times of arrival:

- 0

---

#### Event: Part 4 Arrival - Time 3.08

<table>
<thead>
<tr>
<th>System State</th>
<th>Simulation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Status</td>
<td>3.08</td>
</tr>
<tr>
<td>Number in queue</td>
<td>2</td>
</tr>
</tbody>
</table>

**Event List**

- **Arr. 3.08**
- **Dep. 4.66**

---

#### Times of arrival:

- 0
- 1
Understanding Discrete Event Simulation

Drill Example – Running the Simulation

Event: Part 5 Arrival - Time 4.41

System State

<table>
<thead>
<tr>
<th>Resource Status</th>
<th>Number in queue</th>
<th>Times of arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3</td>
<td>4.41</td>
</tr>
</tbody>
</table>

Simulation Time

<table>
<thead>
<tr>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.41</td>
</tr>
</tbody>
</table>

Event List

<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arr. 4.41</td>
<td></td>
</tr>
<tr>
<td>Dep. 4.66</td>
<td></td>
</tr>
</tbody>
</table>


Understanding Discrete Event Simulation

Drill Example – Running the Simulation

Event: Part 2 Departure - Time 4.66

System State

<table>
<thead>
<tr>
<th>Resource Status</th>
<th>Number in queue</th>
<th>Times of arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
<td>4.41</td>
</tr>
</tbody>
</table>

Simulation Time

<table>
<thead>
<tr>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.66</td>
</tr>
</tbody>
</table>

Event List

<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dep. 8.66</td>
<td></td>
</tr>
<tr>
<td>Arr. 18.7</td>
<td></td>
</tr>
</tbody>
</table>
Understanding Discrete Event Simulation

Drill Example – Running the Simulation

Event: Part 3 Departure - Time 8.05

System State

<table>
<thead>
<tr>
<th>Resource Status</th>
<th>Number in queue</th>
<th>Times of arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Simulation Time

Event List

- Dep 8.26
- Arr. 18.7

Drill Example – Partial Trace of the Process Model Interpretation

<table>
<thead>
<tr>
<th>Time</th>
<th>Process Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.1 Part 1 arrives</td>
<td>First part arrives</td>
</tr>
<tr>
<td></td>
<td>1.2 Part 1 enters buffer</td>
<td>First part enters buffer</td>
</tr>
<tr>
<td></td>
<td>1.3 Part 1 starts service</td>
<td>First part begins processing</td>
</tr>
<tr>
<td>1.73</td>
<td>2.1 Part 2 arrives</td>
<td>Second part arrives and queues for service</td>
</tr>
<tr>
<td></td>
<td>2.2 Part 2 enters buffer</td>
<td>Second part enters buffer</td>
</tr>
<tr>
<td>2.90</td>
<td>1.4 Part 1 completes service</td>
<td>First part is finished</td>
</tr>
<tr>
<td></td>
<td>2.3 Part 2 starts service</td>
<td>Second part begins processing</td>
</tr>
<tr>
<td>3.08</td>
<td>3.1 Part 3 arrives</td>
<td>Third part arrives and queues for service</td>
</tr>
<tr>
<td></td>
<td>3.2 Part 3 enters buffer</td>
<td>Third part enters buffer</td>
</tr>
<tr>
<td>3.79</td>
<td>4.1 Part 4 arrives</td>
<td>Fourth part arrives and queues for service</td>
</tr>
<tr>
<td></td>
<td>4.2 Part 4 enters buffer</td>
<td>Fourth part enters buffer</td>
</tr>
<tr>
<td>4.41</td>
<td>5.1 Part 5 arrives</td>
<td>Fifth part arrives and queues for service</td>
</tr>
<tr>
<td></td>
<td>5.2 Part 5 enters buffer</td>
<td>Fifth part enters buffer</td>
</tr>
<tr>
<td>4.66</td>
<td>2.4 Part 2 completes service</td>
<td>Second part is finished</td>
</tr>
<tr>
<td></td>
<td>3.3 Part 3 starts service</td>
<td>Third part begins processing</td>
</tr>
</tbody>
</table>
Understanding Discrete Event Simulation

- Drill Example – Running the Simulation
  - Time Persistent Statistics

No. of parts in Queue

Busy State of Drilling Press
Randomness in the Simulation

- Drill Example
  - Note that source of Simulation Data can possibly come from recorded behaviour of a real system
  - Is the period of recording a true representation of normal operation?
  - Will input values be always as illustrated in the table?

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Arrival Time</th>
<th>Inter-arrival Time</th>
<th>Service Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>1.73</td>
<td>2.90</td>
</tr>
<tr>
<td>2</td>
<td>1.73</td>
<td>1.35</td>
<td>1.76</td>
</tr>
<tr>
<td>3</td>
<td>3.08</td>
<td>0.71</td>
<td>1.39</td>
</tr>
<tr>
<td>4</td>
<td>3.79</td>
<td>0.62</td>
<td>1.62</td>
</tr>
<tr>
<td>5</td>
<td>4.41</td>
<td>1.28</td>
<td>4.02</td>
</tr>
<tr>
<td>6</td>
<td>5.09</td>
<td>0.70</td>
<td>4.36</td>
</tr>
<tr>
<td>7</td>
<td>19.39</td>
<td>15.52</td>
<td>2.07</td>
</tr>
<tr>
<td>8</td>
<td>34.91</td>
<td>2.15</td>
<td>3.29</td>
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<td>38.06</td>
<td>1.76</td>
<td>2.37</td>
</tr>
<tr>
<td>10</td>
<td>39.62</td>
<td>1.00</td>
<td>3.38</td>
</tr>
<tr>
<td>11</td>
<td>40.82</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Service Time = Random Function

Inter-Arrival Time = Random Function

Inter-Arrival Time = Exponential Distribution Function (mean = 5 min.)

Prob. Density Function
Randomness in the Simulation

- Drill Example

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Arrival Time</th>
<th>Inter-arrival Time</th>
<th>Service Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>1.73</td>
<td>2.50</td>
</tr>
<tr>
<td>2</td>
<td>1.73</td>
<td>1.35</td>
<td>1.76</td>
</tr>
<tr>
<td>3</td>
<td>3.08</td>
<td>0.71</td>
<td>3.39</td>
</tr>
<tr>
<td>4</td>
<td>4.36</td>
<td>2.07</td>
<td>14.28</td>
</tr>
<tr>
<td>5</td>
<td>4.46</td>
<td>3.36</td>
<td>0.70</td>
</tr>
<tr>
<td>6</td>
<td>2.37</td>
<td>2.37</td>
<td>0.70</td>
</tr>
<tr>
<td>7</td>
<td>5.38</td>
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<td>15.52</td>
</tr>
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<td>3.15</td>
<td>3.15</td>
</tr>
<tr>
<td>9</td>
<td>1.73</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>10</td>
<td>0.00</td>
<td>-</td>
<td>0.00</td>
</tr>
<tr>
<td>11</td>
<td>1.73</td>
<td>1.73</td>
<td>1.73</td>
</tr>
</tbody>
</table>

Service Time = Triangular Distribution Function (min = 1, mode = 3, max = 6 min.)

Randomness in the Simulation

- The Necessity of Random Parameter Values
  - Where considerable uncertainty is present in system parameter data values
  - Probability Distribution originates from a statistical analysis of parameter behaviour
    - Various distributions are used to represent various behaviours of system components
    - Important to ensure that the selected distribution fits closely on the statistical data.
Randomness in the Simulation

- The Necessity of Random Parameter Values

Random Inputs → System Model → Random Outputs

Statistical interpretation of Real System Data → Statistical Analysis of Simulation Results

Simulation Replications

- Statistical Analysis of Simulation Results
  - Numerous experimental data can be generated with Probability Functions for the system model inputs
  - Run Multiple Simulated Experiments
    - Will behave similarly following the same probability functions
    - Will not necessarily give the same results
Randomness in the Simulation

- Statistical Analysis of Simulation Results
  - In certain cases, a simulated test may give **extreme results** (e.g. unlikely long processing times, etc.)
    - Far from the expected operating conditions
  - Normal to **run multiple replications**
    - Provide more stability in results interpretations (e.g. through confidence interval evaluation)

Comparing Alternatives

- **Running Experiments under different Conditions**
  - Parameter Values (e.g. Inter-Arrival Times)
  - Control Logic (e.g. changing order in which parts are handled in a queue)
  - We may even want to introduce changes in the simulation model
    - Introducing or Eliminating Buffers
    - Introducing the effect Machine Downtime, etc..
Production Line Example

- **Line Characteristics**
  - 3 stations
  - 2 limited capacity buffers
  - 1 infinite capacity buffer
  - 2 types of parts

**Part A**
Inter-Arrival = 10mins.

**Part B**
Inter-Arrival = Expo (15mins)

Station 3 Failure
- MTTF = 40hrs
- MTTR = 2hrs

Service Time
- **A**: Unif (3.7min)
- **B**: 6min
- **Trian**: min. 2, mode 5.88, max 11mins
- **Expo**: mean 5.5min

10 units 10 units
Production Line Example

- Simulation Objective
  - transient behaviour of buffer queue lengths following a failure of station 3
  - Portion of time a station is blocked
  - Distribution of unit time in the system

Simulation Results
- Running the Simulation for 5 replications
- Simulation duration = 40hr week

<table>
<thead>
<tr>
<th></th>
<th>Station 1</th>
<th>Station 2</th>
<th>Station 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival rate (unit/mins)</td>
<td>1/6</td>
<td>1/6</td>
<td>1/6</td>
</tr>
<tr>
<td>Service rate (unit/mins)</td>
<td>1/5.4</td>
<td>1/5.88</td>
<td>1/5.5</td>
</tr>
<tr>
<td>Utilisation</td>
<td>86%</td>
<td>94%</td>
<td>85%</td>
</tr>
<tr>
<td>Percentage blocked</td>
<td>13%</td>
<td>6%</td>
<td>N/A</td>
</tr>
<tr>
<td>Mean parts at station</td>
<td>46.4</td>
<td>9.9</td>
<td>4.6</td>
</tr>
<tr>
<td>Mean time at station (min)</td>
<td>277.9</td>
<td>61.3</td>
<td>27.5</td>
</tr>
<tr>
<td>Mean parts queued</td>
<td>45.5</td>
<td>9.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Mean time in queue (min)</td>
<td>272.5</td>
<td>55.3</td>
<td>22.0</td>
</tr>
</tbody>
</table>
Production Line Example

- Simulation Results – Buffer 3 queue length

![Buffer 3 queue length chart]

Simulation Results – Buffer 2 queue length

![Buffer 2 queue length chart]
Production Line Example

- Simulation Results – Buffer 1 queue length

Simulation Results – Distribution of Unit Time

Occurrence of Station 3 failure
Production Line Example

- Evaluating impact of increasing buffer sizes
  - Running the Simulation with buffers 2 and 3 having a capacity of 20 units

Part A
Inter-Arrival = 10mins.

Part B
Inter-Arrival = Expo (15mins)

Production Line Example

- Simulation Results (2) – Buffer 3 queue length
Production Line Example

- Simulation Results (2) – Buffer 2 queue length

![Graph showing Buffer 2 queue length](image)

- Simulation Results (2) – Buffer 1 queue length

![Graph showing Buffer 1 queue length](image)
Production Line Example

- **Simulation Results (2) – Other Results**
  - % blocking time for station 1
    - Reduced from 13% to 5%
  - % blocking time for station 2
    - Reduced from 6% to 2%
  - Average Throughput per week
    - Increased from 380 to 399 (with an absolute max theoretical throughput of 408 parts)

---

Production Line Example

- **Simulation Results (2) – Distribution of Unit Time**

<table>
<thead>
<tr>
<th>Part Time in system (hrs)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2</td>
<td>20%</td>
</tr>
<tr>
<td>2 - 4</td>
<td>14.6%</td>
</tr>
<tr>
<td>4 - 6</td>
<td>18.5%</td>
</tr>
<tr>
<td>6 - 8</td>
<td>38.4%</td>
</tr>
<tr>
<td>8 - 10</td>
<td>8.5%</td>
</tr>
<tr>
<td>&gt; 10</td>
<td>0.0%</td>
</tr>
</tbody>
</table>