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SIMULATION-BASED SUPPORT TOOL FOR OPERATOR PERFORMANCE IN BATCH MANUFACTURING

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ABSTRACT
In industry, the workload and utilization of shop floor operators is often misunderstood. In this paper, we will present several real case studies, using Discrete Event Simulation (DES) models, which allow us to better understand operators in a batch manufacturing environment. The first study investigates labour in a machining plant consisting of multiple identical CNC machines that batch produce parts. The second study investigates labour in an eight station, gravity die casting rotary table. The results from these studies have shown that there can be potential improvements made by the production planners in the current labour configuration. In the first case study, a matrix is produced that estimates what the operator’s utilization levels will be for various configurations. From this, the preferred operator to machine ratio over a range of cycle times is presented. In the second study, the results have shown that by reducing the casting cycle time, the operator would be overloaded. A discrete event simulation of these two cases highlighted areas that were misunderstood by plant management, and provided them with a useful decision support tool for production planning.

Key Words: Ergonomics & Human Factors, Simulation, Production Management.

1. INTRODUCTION
The factors that influence an operator’s performance in manufacturing are often misunderstood. With a large emphasis nowadays on process improvement and cost reduction, any performance improvement for a company is looked upon quite seriously. This work has developed out of a research program started with Pacifica Group Technologies, a R&D subsidiary of Pacifica Group Limited. One area identified within the main subsidiary operations company, PBR Automotive - a brake manufacturer, that required better understanding was operator performance. There were many pre-conceived ideas about the capabilities of operators in the machining and casting areas, and a thorough investigation was required. The purpose of the investigations was to help the company understand how the operators can be better utilized, and what can be done to balance their workload.

Some other applications with similar tasks include where a discrete event simulation was used to solve a load balancing problem in a semiconductor fabrication facility (Monch et al., 2001). A model was used to determine optimum job release times in a bottleneck area of photolithography. Also, an interactive production planning system was constructed for use in the electronics industry (Johtela et al, 1997). This used simulation to better balance the workload for the operators and machines. Simulation is used as a decision support tool for a scheduling task by (Gupta et al, 2002). The performance of this plant is misunderstood, using simulation; the systems load and sequencing is analysed and a better schedule is developed.
for implementation on the shop floor. These studies have been applied in manufacturing flow-shop type environments, where machines are organised according to a specific processing order. Simulation based support tools have also been applied in the area of supply chain logistics. A simulation based support system is proposed by (Ganapathy et al, 2003) to optimize planning for a supply chain process and ensure the correct decisions are made the first time.

Production in our application is somewhat different to the examples given. The jobs are performed in batches, ours is a single stage process, and the jobs are released and performed in parallel. The problem described in (Turkan et al, 2003) is similar to this, where a series of non-identical CNC machines produce parts in parallel. This situation uses multiple non-identical CNC machines, hence some machines are physically different, for example the maximum horsepower varies, the tooling systems are different, loading/unloading times vary between machines and the operating costs are machine dependent. The key difference in our application is that all machines are exactly the same, each machine has a complete set of tooling, the load/unload times are identical for each machine and the processing time for each part type remains the same, no matter which machine is used.

Within the organisation, we have performed two case studies; these include a machining cell and a gravity die casting cell. In the two cases, individual discrete event simulation models were developed.

The first case study, based on a machining cell, includes multiple CNC machines that batch produce brake components. The base model replicates the current setup within the plant, where one operator is assigned to four identical machines. The role of the operator is to load an un-machined casting into the fixture of a machine, then remove the machined casting from that machine and place it on an output conveyor. The operator then completes the same process for the other machines they are assigned to. A cell is arranged around a line of 18 identical machines, with two columns and 9 machines per column, as shown in Figure 1, which has a number of operators working the line.

The second case study is based on an aluminium gravity die casting cell. This cell consists of eight tilt casting stations that are mounted on top of a round rotating table. The casting moulds rotate past a dosing station where they are dosed, go through a cooling process and then are unloaded at another point within the cell by an operator. This operator then places the parts into a cooling tower located next to the table and then into a cut-off saw after sufficient cooling time, as shown in Figure 2.

Figure 1. Case Study One (CNC Machining Cell)
Figure 2. Case Study Two
(Gravity Die Casting Cell)

2. PROJECT OBJECTIVES
The purpose of these case studies is to investigate how the labour workforce can be better utilized within the plant. The difficult part in our situation is that we do not fully understand the labour/machine relationships within the system. There are various labour and production related issues that have restricted our ability to make physical changes to the systems under investigation. A number of time studies and existing data, therefore, have been used in order to create a simulation model of the system, and make changes “digitally”. The measured outcomes expected from the simulation model will be based around operator utilization and production output. The overall aim was an attempt to balance all operators’ workloads to reasonable levels, whilst ensuring that the production output does not drop. There may be situations where some operators are overworked, which potentially can cost the company money and other cases where operators are under worked, and therefore an area for potential improvement.

3. THE SIMULATION MODEL
A series of discrete event models (Banks et al, 2000) have been created using a commercially available DES package called QUEST, by Delmia. The next two sub-sections will provide more detail on the formulation of each model.

3.1. Machining Cell Model
The machines used are identical CNC machines. A CNC machine consists of a front and a back compartment that are physically isolated. A rotary table transfers parts from the front section to the back and vice versa. In the back section, the parts are machined. While machining is performed in the back section, the doors at the front of the machine can be opened, and the previously machined part can be replaced by the operator, ready for the next cycle. When new parts are loaded into the front of the machine, and the doors are closed, the rotary table then rotates at the end of the machining cycle. This type of machine gives the operator a large time window to replenish the machined parts with un-machined ones. When the operator attends to the machine within this time window, the output of the machine is not affected by waiting for the operator to complete their tasks, and high volumes of production can be achieved.
3.2. Gravity Die Casting Cell Model
In the gravity die casting cell, a round table constantly rotates, and eight tilting gravity die
casting stations are mounted to it. The tilter is in the vertical position while it rotates past a
doser that pours molten aluminium into a ladle on the front of the tilter. The tilter then slowly
rotates to the horizontal position, where aluminium runs into the die. The station remains in
the horizontal position while the die contents solidify. Then while the table is continually
rotating, the station tilts up, where the parts are ejected onto an unloading arm. The operator
then removes waste from the ladle, and picks up the castings from the unloader, places them
into a cooling tower, next to the rotating table. Two previously “cooled” parts are then
removed from the tower, one at a time and placed into the saw. After this, a start button on
the tilting station is then pressed, and the sequence for that station begins again. This process
occurs for each of the eight casting stations, with the full rotation of the casting table taking
about six to seven minutes.

4. SIMULATION INPUTS
In the following section we will discuss the inputs used in the simulation of the two
manufacturing processes. During the construction of the simulation models, detailed CAD
drawings of the manufacturing plant layout were used to ensure accurate positioning of all the
devices.

4.1. General Labour Related
In the labour elements of our simulation models, there are several key inputs used to “mimic”
a real life operator. The operators schedule is based on the companies U.S. personnel
calendar that includes three shifts, working for 245 days with work stopping during the
weekends. A provision for operator tea and lunch breaks was also included. When an
operator is unavailable due to a break, the machines keep processing until the end of their
cycles, and then wait until the operator replenishes the parts.
A time study of the operators walk speed, load and unload times was not available,
therefore a discussion with plant management was held and assumptions for these variables
were used. For each of the models, an operator’s walk speed was estimated at 0.5 metres per
second.

4.2. Machining Cell Inputs
The processes performed by the operator in the machining model involve the repetitive task
of:
- picking up two parts from the input conveyor,
- placing them into the machine,
- then removing two machined parts from the machine unloader
- And placing them on the output conveyor.
In table 1, estimates of these times were made by experienced manufacturing engineers. For
the purpose of our initial simulation, these values are modelled as constants. They are
generous estimates for the operations. To observe the effect of variability in these times, a
sensitivity analysis was performed afterwards using a triangular distribution, with a mean of
4 seconds, and an estimated minimum value of 4 seconds and a maximum of 6 seconds. The
result of this investigation showed less than a 0.5% variation in the operator’s utilization
levels.
Table 1. Labour process times for machining model.

<table>
<thead>
<tr>
<th>Task</th>
<th>Time (secs)</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Place two parts into machine</td>
<td>5</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Pickup two parts from machine</td>
<td>5</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Pickup two parts from conveyor</td>
<td>5</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Place two parts onto conveyor</td>
<td>5</td>
<td>Deterministic</td>
</tr>
</tbody>
</table>

The cycle times for the CNC machines in our simulation are based on time studies performed by the manufacturer. These values are modelled deterministic, as this process has very low variability. A text file is used to adjust the cycle time of each machine.

In table 2, the breakdowns used in the simulation are summarised. These breakdowns include short term events such as tool monitoring alarms that occur when dedicated software detects that the tool is not operating correctly and stops the process to allow for the defective tool to be changed. Every tool has a limited tool life, and therefore a failure is used to replicate the event of a tool change being required. There are also longer term downtimes that occur; these include CNC machine and the coolant system breakdowns. A preventative maintenance plan, taken from the “actual plant” is used in our model. All stochastic events are modelled as triangular distributions, shown in Table 2 as Tri (Minimum, Mean, Maximum).

Table 2. Machining model downtime information

<table>
<thead>
<tr>
<th>Downtimes</th>
<th>Repair Time (minutes)</th>
<th>Time to Failure (minutes)</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool monitoring - software alarm</td>
<td>10</td>
<td>Tri(480, 720, 900)</td>
<td>Stochastic</td>
</tr>
<tr>
<td>Worn Tool Changes</td>
<td>12</td>
<td>Tri(100, 480, 720)</td>
<td>Stochastic</td>
</tr>
<tr>
<td>Machine Breakdowns</td>
<td>123.6</td>
<td>Tri(28800, 43200, 50000)</td>
<td>Stochastic</td>
</tr>
<tr>
<td>Coolant System Breakdown</td>
<td>493.8</td>
<td>Tri(33333, 43200, 50000)</td>
<td>Stochastic</td>
</tr>
<tr>
<td>Preventative Maintenance (PM)</td>
<td>n/a</td>
<td>As per actual PM plan</td>
<td>Deterministic</td>
</tr>
</tbody>
</table>

4.3. Gravity Die Casting Cell Inputs

The process performed by the operator in our casting simulation involves repeating the following procedure for each die casting station. This process consists of:
- firstly removing waste from the pan on the casting station,
- then picking up two hot castings from the unloader (a time saving device mounted onto the casting station),
- walking and placing the castings into a cooler, which then causes two “cooled” parts to be ejected from the cooler,
- picking the cooled castings up, walking over, and placing them into the cut-off saw, one at a time.

The procedure is repeated for each of the eight casting stations that are located on the rotating table.

The load and unload times for these operations are shown in table 3, which are taken from time studies, provided from the manufacturing engineer.

Table 3. Labour process times for casting model.

<table>
<thead>
<tr>
<th>Operation Description</th>
<th>Time (secs)</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remove waste from die</td>
<td>4</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Remove 2 castings from tray and place onto tray</td>
<td>6</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Slide castings to cooler</td>
<td>6</td>
<td>Deterministic</td>
</tr>
<tr>
<td>Remove two castings from cooler and place in saw</td>
<td>6</td>
<td>Deterministic</td>
</tr>
</tbody>
</table>
There are eight tilt casting stations that are mounted to the round rotating bed. These run independently to the rotary table; however their total cycle time is same. The cycle times of these devices are modelled as constants, as there is no significant variability from cycle-to-cycle. The current cycle time within the plant for the rotary table is six minutes, which is one 360 degree rotation. We have included provisions in the model to be able to adjust the cycle time of the table and the tilting stations, so that we can observe how the operator's workload varies when the cycle time is reduced to 5.5 minutes. Further provisions have been included to turn each of the eight stations on or off, to observe the effect that running more or less tilting stations has on the operator.

Each tilt casting station contains a two-part die. These have a limited life before the quality of the castings is compromised. The number of castings that a die can produce before it requires changing has been pre-determined by manufacturing engineers; this optimum value is referred to as the die life. The die life is set at a constant amount. When the die reaches its life, the rotating table stops at a specific point, the whole tilt casting station is replaced with another one that has been prepared offline. This time used to represent the time taken to changeover the station is deterministic.

5. SIMULATION ASSUMPTIONS

The following section describes any issues that arose during the study, and any other assumptions that we needed to make during the modelling process.

5.1. Machining Cell Modelling

Within the plant, up until now, there has been no defined walk path for the operator to follow in a machining cell. Therefore, with the help of manufacturing engineers, a strategy for the operators was defined. The simulation model of a one operator, to four machine cell is shown in figure 3. The operator is responsible for loading and unloading parts for each of these four machines. The strategy for the operators was based upon this cell, where the aim was to provide operators with an optimum walk path.

![Figure 3. One operator, four machine cell.](image)

The logic flow for the operators walk path is shown in figure 4. The aim of this strategy is to ensure the operator walks in a cyclic manner, from one machine to the next.
The machining operations we are investigating are one stage in the overall manufacturing process. There were no investigations or information available regarding part flow between these different processes. For instance, we have assumed that the casting area produces sufficient parts for us to continue machining.

Due to several downtimes that have long mean time between failures, and long failure downtimes until repair, a large simulation run time was required to ensure the effects of these events were measured in the system. Therefore each machining simulation was run over a time period of one year.

5.2. Gravity Die Casting Cell Modelling

In the modelling of the casting cell, the issue of molten aluminium replenishment rates and fluid levels had arisen. The plant is setup such that solid aluminium is melted using large tower furnaces, and transported to the casting cell doser using forklifts. To model the replenishment of the doser is quite complex; therefore, for the purposes of this study, we assumed that the dosers fluid levels are sufficiently maintained.

A simulation in this investigation was performed for thirty days, or approximately one month. At the time of the investigation, there was no detailed information about the downtimes that occur. After discussions with experienced manufacturing engineers within this area, it was concluded that from their experience, the time between failures was relatively large. Therefore, in this study, we are only focusing on the operator’s workload during the cells normal operation, when breakdowns are not occurring.

6. VALIDATION

Using an eight-step model validation procedure (Sargent, 2001), the following basic validation tasks were used by the model development team.

A base model was developed for each case study, and the model validation process was performed to determine that the part output resembles that of the actual system. The base model did not include any failures, downtime or scheduled outages for the system. Using results obtained from simulation runs, the output was compared to that of the real system.
With the assistance of manufacturing engineers, the outputs were deemed to be somewhat similar to what they had calculated. Using the three dimensional model interface, a walkthrough of the model was conducted. The model logics, routing and operation of the model was performed.

Using the base model previously developed, we then included various stochastic and deterministic failures into the model. Using animation and traces, correct failure operations were identified. There were then various simulation runs, with the results compared to the results obtained from the base model. The results and 3D visualization were reviewed with the manufacturing engineers and compared to the previous plant performance and deemed to be acceptable.

The model validation technique used by (Williams, Chompumung, 2002) was also applied as a final confirmation. This technique assumes that if there are no downtimes or delays occurring during a particular simulation interval, then the measured time to produce a part should be the same as the cycle time of the machine. Our model was configured so that each machine in the cell was running at a different, but known cycle time. The time taken to produce a part was measured, when no failures or delays had occurred. The measured times matched the cycle time for each machine, confirming the validity of our simulation model.

7. RESULTS and DISCUSSION

After constructing and validating models of the machining and casting cells, various scenarios were run, and the following results were obtained.

7.1. Machining Cell Results

Using the developed DES model, various experiments have been designed to help us better understand the operators' performance. Our experiments consisted of three sets of simulation runs of the DES model. The first set of experiments involves setting the model up with one operator assigned to four machines. The second set involves configuring the simulation with one operator assigned to five machines, and the third with one operator and six machines. For each of the three sets of simulation runs, the cycle time was varied from 150 seconds up to 260 seconds, in increments of ten seconds. These cycle times represent the range of cycle times for all the products that would be potentially machined in this cell. The results from each of these sets of simulations are shown in Table 4.

<table>
<thead>
<tr>
<th>Cycle Time (secs)</th>
<th>No. of Machines per Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>150</td>
<td>80%</td>
</tr>
<tr>
<td>160</td>
<td>75%</td>
</tr>
<tr>
<td>170</td>
<td>70%</td>
</tr>
<tr>
<td>180</td>
<td>67%</td>
</tr>
<tr>
<td>190</td>
<td>63%</td>
</tr>
<tr>
<td>200</td>
<td>60%</td>
</tr>
<tr>
<td>210</td>
<td>58%</td>
</tr>
<tr>
<td>220</td>
<td>55%</td>
</tr>
<tr>
<td>230</td>
<td>53%</td>
</tr>
<tr>
<td>240</td>
<td>50%</td>
</tr>
<tr>
<td>250</td>
<td>49%</td>
</tr>
<tr>
<td>260</td>
<td>47%</td>
</tr>
</tbody>
</table>
After collating the results of our simulation experiments, the operator utilization versus cycle time has been plotted for each operator to machine configuration. There is a slight non-linear relationship between the operator utilization and cycle time, as shown in Figure 5.

![Figure 5. Operator Utilization versus machining cycle time.](image)

One of the preconceived ideas within the company was that an operator would be overworked if they were assigned to any more than four machines. This has been a contentious issue, and with the use of the DES model, we have been able to use the 3D visualization to disprove this theory for a range of situations. After further review of the simulation and the results with experienced manufacturing engineers within this area, a limit for the maximum allowable operator utilization was set at 80%. Using this limit, a series of shaded areas have been included within the operator matrix, as shown in Table 4. These shadings provide a guideline for production planners, aiming at minimising the number of operators required. These results tell us that a one operator to a four machine cell is best suited to cycle times of between 150 and 180 seconds. One operator to a five machine cell is best suited to cycle times of between 190 and 220 seconds. One operator to six machines is best suited for machines running cycle times of between 230 and 260 seconds. This summary matrix has proved highly beneficial as a decision support tool for effective production planning.

### 7.2. Gravity Die Casting Cell Results

Constant improvement is an important task to maintain competitiveness within the industry. An effective, low cost solution is to put inefficiently used equipment to better use. A cycle time reduction and an improvement in the utilization of the casting stations are the obvious areas for further investigation in this case. The design of our experiments was aimed at measuring how the operator is affected by making such proposed changes. There were three experiments designed, using our DES model to measure these effects.

The first is a replica of the current setup within the plant. This was used as the benchmark to compare improvements against. This setup uses a six minute cycle time for the casting stations, and only uses six of the eight available tilting stations located on top of the rotating turntable. In the second experiment we will observe what the effect will be on the operator if we wish to increase the throughput within the cell. This was done by utilizing all eight of the casting stations on the table. A cycle time reduction from six minutes down to five and a half minutes was also implemented. A significant increase in the operators workload is expected, however we were unsure just how significant this would be. A third experiment was then
performed, as an extension from the second one. It was expected that the operator’s workload in the second scenario may approach critical levels, so the third experiment aimed at reducing the operators workload by limiting the number of tasks performed. This was done by replacing the existing saw in our model, with a more efficient dual fixture saw. This type of saw allows the operator to take two parts (instead of one at a time) from the cooler and load them both into the saw.

The results from the three experiments are shown in Table 5. With the current setup within the plant, the operator is 61% utilized. By reducing the cycle time of the casting stations to five and a half minutes, and running all of the 8 casting stations, the output is increased by around 45%. The problem associated with this scenario, as we anticipated, is that the operator is now over-utilized at 88%. From the previous investigation within the machining cell, we assumed that around 80% would be the maximum allowable operator utilization; therefore the operator’s workload must be reduced. Therefore, a third experiment included a dual fixture saw, which provided an effective solution to the problem. The same production output was maintained using the new saw, however the operator’s utilization was reduced by 24%.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Output (parts per month)</th>
<th>Operator Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>85,660</td>
<td>61 %</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>124,106</td>
<td>88 %</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>124,106</td>
<td>64 %</td>
</tr>
</tbody>
</table>

8. CONCLUSIONS

The area of operator performance is often misunderstood in the manufacturing industry. Using a commercially available Discrete Event Simulation package, we have performed two case studies within an automotive brake manufacturing plant. In the first case study we have shown how a simulation model can be developed to understand how the cycle time and number of machines per cell affects the operator’s workload. Using the simulation model, we varied these two factors and measured the effects. An operator selection matrix was produced, which is an important tool for management and production planners when aiming to achieve the optimum plant configuration. The second case study has shown how simulation can effectively be used to better understand how changes in the plant would affect the operator’s workload. A cycle time reduction and an improvement in the utilization of the casting stations was suspected to have a significant effect on the operators workload, however this study has provided an accurate analysis of the effects. Using a 5.5 minute cycle time, all eight casting stations, and installing a dual fixture saw, a 24% increase in cell output was obtained, with only a 3% increase in the operator’s workload. This is a good justification for the purchasing of a new saw for the cell. An improved understanding of the operator’s performance has now be gained after the completion of these two particular case studies, and has provided management with a decision support tool for the planning and scheduling of the facilities.

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personnel at Pacifica who helped in obtaining the necessary information and data to make the simulations realistic.

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