IE 5322 – Simulation and Optimization Project

Section: 001
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Problem Definition

New World Energy (NWE) is planning to establish a new photovoltaic panel production facility in Akureyri, Iceland whose intended production capacity per month is 1.8 Megawatt. In Akureyri, the presence of highly pure crystallized silicon deposits, geothermal electric power generation capability and the government incentives make manufacturing there an attractive proposition.

The planning and design of the proposed manufacturing facility is necessary to ensure the proper allocation of $ 500,000 / month towards increasing the production capacity and a simulation model is an excellent tool that can be used for this. Mr. Heinrich Grünfuror, who is the Chief Technical Officer (CTO) at NWE, would like to know the following:

1. Simulation project plan
2. Graphical representation of production processes
3. Deterministic estimation of the design of the facility (based on calculations in excel)
4. Capital investment needed to develop a pilot production facility
5. Capital investment needed to achieve the production target (1.8 Megawatt/month)
6. Capitalization plan to bring Akureyri facility up to full capacity with a monthly budget of $ 500,000 in 12 months
7. Staffing requirement for the pilot production facility
8. Staffing levels and shift patterns required during each phase of production expansion
9. Sales price of each PV cell required to earn a minimum 20% rate of return on invested capital

Below are the primary activities needed to support the development of a simulation model:

1. Problem Formulation
    - Outlines the problem, deliverables and the questions that will be answered
2. Project Planning
    - Present a Gantt chart that shows the project schedule
3. System Definition
    - Understand NWE's other production operations (Work with Mr. Björn Eyjafjallajokull)
    - Develop a process flowchart and a deterministic excel design estimate
4. Conceptual Model Formulation
    - Discuss the simulations constructs needed to develop a discrete event simulation model
5. Preliminary Experimental Design
    - Identify system performance measures and system variables of interest
    - Design experiments to answer questions outlined by Mr. Heinrich Grünfuror
6. Input Data Preparation
    - Document input data that can be used to model the facility by consulting Mr. Björn Eyjafjallajokull
7. Model Translation
    - Build the model
8. Model Verification
    - Ensure the logic and input data used to build the model are correct

9. Model Validation
    - Work with Mr. Björn Eyjafjallajokull to ensure the model represents the real facility adequately
10. Final Experimental Design
    - Finalize the simulation runs and the run length needed to calculate the system performance measures
11. Experimentation
    - Run the experiments and document the results
12. Analysis and Interpretation
    - Analyze the model output and identify bottlenecks and resources needed in each month to increase production
13. Implementation
    - Recommendations based on the results
    - Provide answers to Mr. Heinrich Grünfuror's questions

Project Planning

The execution timeline for the project activities is shown in Table 1.

Table 1 Project Schedule

Task Name	***Start Date***	***End Date***	***Duration (Days)***
Problem Formulation	2/7/24	2/12/24	5
Project Planning	2/12/24	2/18/24	6
System Definition	2/18/24	2/23/24	5
Conceptual Model Formulation	2/23/24	3/1/24	7
Preliminary Experimental Design	3/1/24	3/7/24	6
Input Data Preparation	3/7/24	3/11/24	4
Model Translation	3/11/24	3/25/24	14
Model Verification	3/25/24	3/31/24	6
Model Validation	3/31/24	4/9/24	9
Final Experimental Design	4/9/24	4/13/24	4
Experimentation	4/13/24	4/15/24	2
Analysis and Interpretation	4/15/24	4/21/24	6
Implementation	4/21/24	4/26/24	5
		Total Duration	79

Technology Exporters USA will have to meet with Mr. Björn Eyjafjallajokull during various phases of the project for hours as stated below:

- System Definition – 10 hours
- Input Data Preparation – 8 hours
- Model Validation – 18 hours

Other resources that will be used by Technology Exporters USA include Witness simulation package, Windows laptop with a 16 GB RAM and 1.7 GHz 12^{th} Gen Intel Core i7 processor. The consultation charges for the project will be $ 31,600 as we will be working 4 hours each day for 79 days on this project and our fee is $ 100 per hour.

The Gantt chart in Figure 1 shows the planned duration and time spent on each activity.

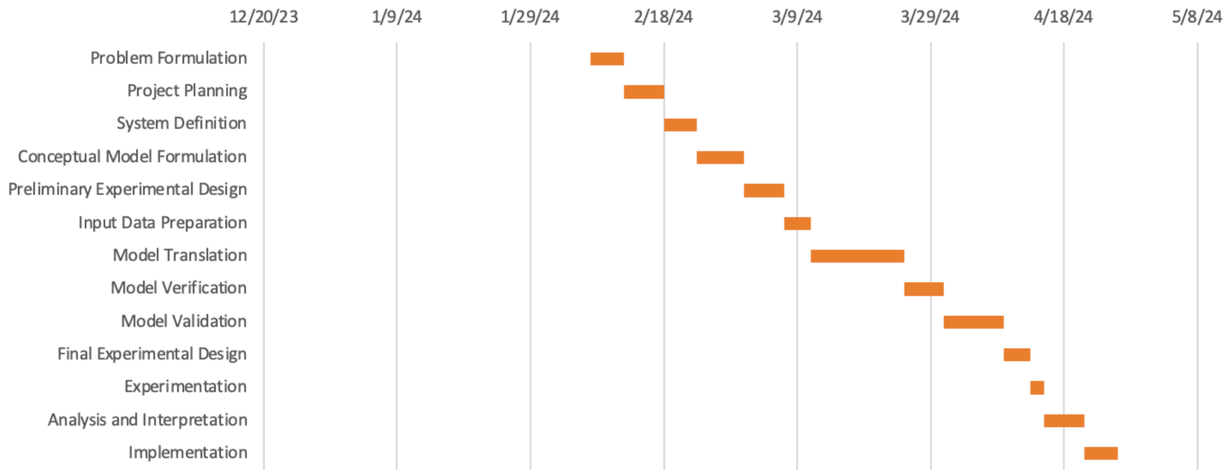

Figure 1 Gannt Chart

The tasks shown in Table 1 were not executed precisely during the dates shown in it. However, the order in which the tasks were completed is correct and the number of man-hours each task took was the same as the estimate. The system was broken down into sub models as shown in the conceptual model design section and they were built first to see if the logic worked the way it is intended. Then the sub models were connected into a single model to create the base model.

The model translation took a little less than 11 days but was challenging. Model verification was an iterative task which continued in parallel with the model translation process. The model was then validated with Dr. Huff's model which helped uncover some flaws in my model logic and correcting the modeling errors, helped validate the model and my model production number matched the validated model production numbers.

The experimentation task took longer than expected and took a lot of effort. Analysis and implementation time estimates were correct. Writing this report is a task which was not accounted for in the project planning and this task also took about four days to finish (6 hours each day).

The tasks listed in Table 1 helped me stick to the process of developing a simulation model which helps answer specific questions described in the problem definition phase.

System Definition

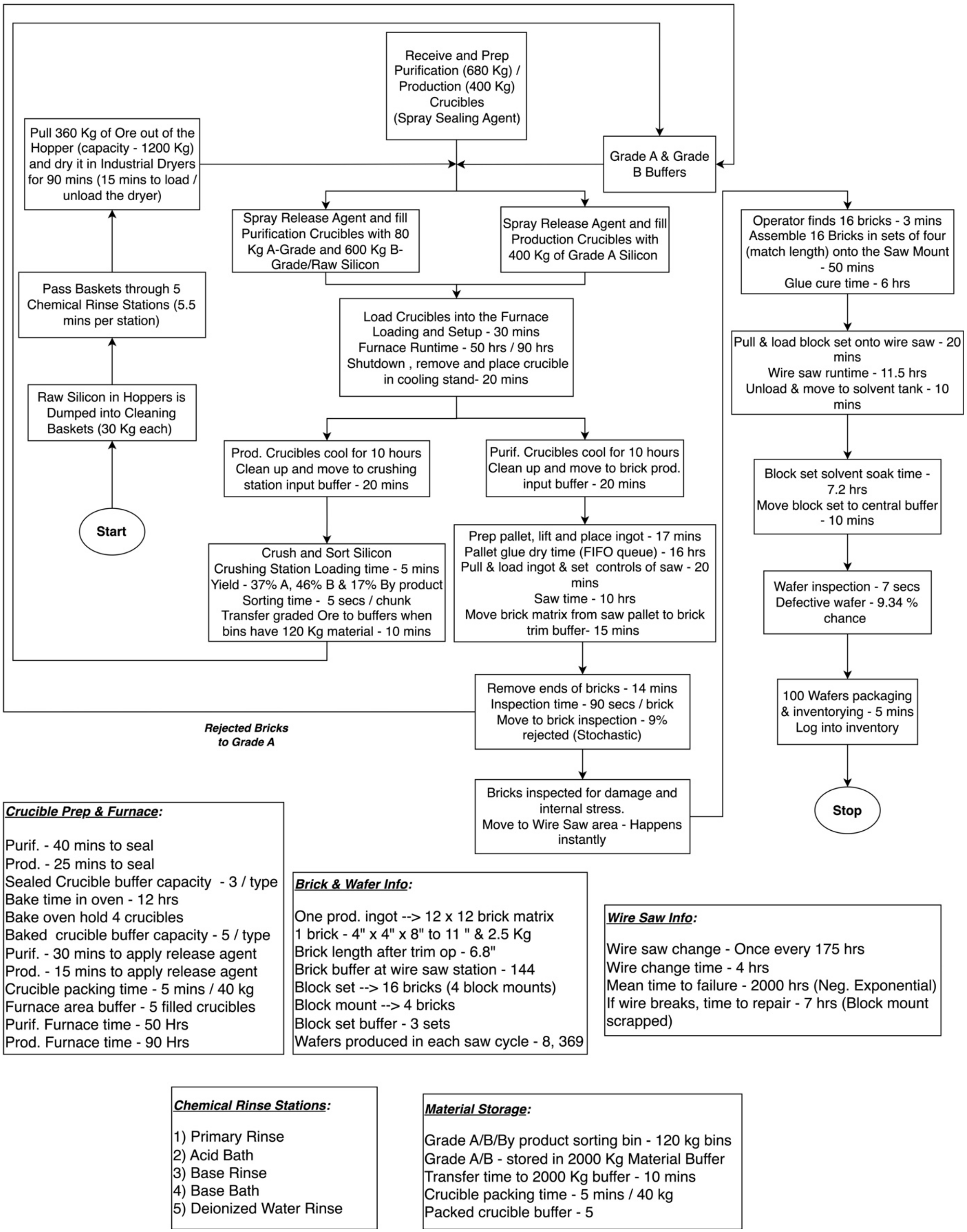

Figure 2 Process Flow Chart

Conceptual Model Design

This section describes the features and modeling constructs of the simulation tool which would be used to model sections of the facility.

Table 2 Conceptual model of raw ore cleaning

<table>
<tr><th colspan="2">Real-world element</th><th>Witness constructs</th><th>Simio constructs</th></tr>
<tr><td colspan="2">30 Kg Raw ore</td><td>Part</td><td>Model Entity & Server</td></tr>
<tr><td colspan="2">Ore Cleaning Machine</td><td>Multi-station Machine (Cycle Time: 5.5 mins, Stations: 5)</td><td>5 Servers (Cycle Time: 5.5 mins per server)</td></tr>
<tr><td rowspan="2">Hoppers</td><td>Wet</td><td>Buffer (Capacity: 40)</td><td>Output buffer of Ore Cleaning Machine (Capacity: 28) & Combiner (Capacity: 12)</td></tr>
<tr><td>Dry</td><td>Buffer (Capacity: 40)</td><td>Output buffer of Dryer (Capacity: 40) and Separator</td></tr>
<tr><td colspan="2">Dryer</td><td>Multi-station Machine (Qty:12, Cycle Time: 720 mins)</td><td>Server (Cycle Time: 720 mins)</td></tr>
<tr><td colspan="2">Ore Cleaning Operator</td><td>Labor</td><td>Resource</td></tr>
<tr><td colspan="2">Path</td><td>Input/Output rules</td><td>Connectors & Sink</td></tr>
</table>

To model raw ore cleaning & drying process, Witness and Simio would require different constructs and approach as seen in Table 2. While Witness has multiple machine types like batch, multi-cycle and multi-station which make modeling easy, Simio needs additional constructs like combiners and separators for batch processing and multiple servers to model rinse stations. Hence, Witness has been chosen to model the project hereon. The buffer capacity was 40 earlier as each entity was set to be 30 Kg. However, in the brick inspection section, when some bricks are rejected, they are sent back to Grade A buffer and each brick weighs 2.5 kg. Hence, the weight of each entity of Raw ore, Grade A, Grade B and by product was later changed to half Kg and buffer capacities were adjusted accordingly.

Table 3 Conceptual model of receiving and prepping crucibles

Real-world element	***Witness constructs***
400 Kg Production Crucibles	Part
680 Kg Purification Crucibles	Part
400 Kg Sealed Production Crucibles	Part
680 Kg Sealed Purification Crucibles	Part
400 Kg Baked Production Crucibles	Part
680 Kg Baked Purification Crucibles	Part
Crucible Sealing agent application	Single Machine
400 Kg Sealed Crucible Buffer	Buffer (Capacity: 3)
680 Kg Sealed Crucible Buffer	Buffer (Capacity: 3)
Crucible Bake Oven	Batch Machine (Qty: 4, Cycle Time: 720 mins)
400 Kg Baked Crucible Buffer	Buffer (Capacity: 5)
680 Kg Baked Crucible Buffer	Buffer (Capacity: 5)

Crucible prep. operator	Labor

Crucible receiving and prep process has been shown in Table 3 with its modeling constructs in Witness. A single machine was used to process crucibles and the sealed crucibles are sent to their respective buffers. A batch machine was used to model the oven which processed four crucibles at a time and sent them to respective buffers after the crucibles complete their bake time. The crucibles change their part type as they are sealed and baked.

Table 4 Conceptual model of filling and prepping crucibles

Real-world element	***Witness constructs***
680Kg Filled Crucibles	Part
400Kg Filled Crucibles	Part
0.5 Kg Grade A Silicon	Part
0.5 Kg Grade B Silicon	Part
0.5 Kg Grade A Silicon Buffer	Buffer (Capacity: 8000)
0.5 Kg Grade B Silicon Buffer	Buffer (Capacity: 8000)
0.5 Kg By Product Buffer	Buffer (Capacity: 10000)
By product shipper	Single Machine
Fill Purification/Production Crucible	Multi cycle Machine
Furnace input Buffer	Buffer (Capacity: 5)

The process of prepping and filling the baked crucibles is modeled as shown in Table 4. Grade A and Grade B silicon is stored in buffers of size 8000 as each entity is 0.5 Kg. The by product is stored in a buffer and is shipped out of the facility using a zero-time single machine. A single multi-cycle machine is used to fill both production and purified crucibles using attributes to store quantities of grade A and B or raw silicon with the baked crucibles. Baked production crucibles have 800 as the grade A quantity and 0 as the remaining quantity whereas baked purification crucibles have 160 as grade A quantity and 1200 as the remaining grade B or clean ore quantity. As the crucibles need to be sprayed with release agent before they are filled, the spray time of respective crucibles are also stored as attributes with the backed crucibles. After the crucibles are filled, the part type changes from baked to filled crucibles in the last cycle of the multicycle machine and the filled crucibles are stored in a furnace input buffer.

Table 5 Conceptual model of furnace area

Real-world element	***Witness constructs***
Production Ingot	Part
Purified Ingot	Part
Chunks	Part
Furnace	Multi cycle Machine
Cooling Stand	Multi cycle Machine
Crushing & Sorting Machine	Multi cycle Machine
Grade A / Grade B / By product Bins	Buffer (Capacity: 240)
Grade A / Grade B / By product move to Buffers	Batch Machine
Crushing station input buffer	Buffer (Capacity: 1)
Brick production input buffer	Buffer (Capacity: 1)

Furnace operator	Labor

The furnace area with the cooling stand, crushing/sorting station and the grade A, grade B and by product bins were modeled as shown in Table 5. Filled crucibles are pulled into the furnace and the cycle time for the furnace is set based on the value of the "Furnace_cycle_time" attribute carried the filled crucibles. The cycle time is 50 hours for the purification crucibles and 90 hours for the production crucibles. Once the furnace processes a filled crucible, it takes 20 minutes for the furnace to be shut down and then the filled crucible is sent to the cooling stand where the crucibles change to production or purified ingot after cooling when the crucibles shatters. The purified ingots are sent to crushing input buffer and the production ingots are sent to brick production input buffer. The crushing and sorting station receives the purified ingot and turns it into chunks which are sorted and stored in respective bins which will be moved to their respective buffers. This move is modeled by batch machines with a cycle time of 10 minutes. The crushing station takes 226.66 minutes to sort all chunks produced by one purified ingot.

Table 6 Conceptual model of brick production and trim area

Real-world element	***Witness constructs***
Brick	Part
Ingot prep	Multi cycle Machine
Dicing saw	Multi cycle Machine
Move bricks	Batch Machine
Brick trim input buffer	Buffer (Capacity: 144)
Brick trimming	Single Machine
Brick trim output buffer	Buffer (Capacity: 144)
Brick inspection and sizing	Single Machine
Defective brick buffer	Buffer (Capacity: 1000)
Good brick buffer	Buffer (Capacity: 144)
Move defective bricks to Grade A buffer	Multi-cycle machine
Brick production operator	Labor

The conceptual model design of the brick production, trimming and inspection area is shown in Table 6. A single production ingot is pulled and glued to a pallet in the ingot prep machine. The dicing saw machine pulls the pallet from the ingot prep machine and cuts the ingot into 144 bricks. This machine is modeled using a multi-cycle machine with setup time allocated to the dicing machine. Then the bricks are moved to the brick trim input buffer using a batch machine to simulate a cart carrying 144 bricks. The brick trimming machine pulls a single brick and processes it and sends it to brick trim output buffer. The brick inspection machine is also a single machine processing one brick at a time and sending it to either defective brick buffer or good brick buffer.

Table 7 Conceptual model of wire saw and wafer production area

Real-world element	***Witness constructs***
Block set	Part
Block mount	Part
Wafer	Part
Stacked wafer box	Part

Pull cart to block set input buffer	Single Machine
Block set input buffer	Buffer (Capacity: 144)
Assemble block sets	Multi-cycle machine
Block set output buffer	Buffer (Capacity: 3)
Wire saw	Multi-cycle machine
Solvent tank	Multi-cycle machine
Unload solvent tank (If needed)	General Machine
Central buffer	Buffer (Capacity: 1)
Get mounts when needed	Multi-cycle machine
Individual wafer buffer	Buffer (Capacity: 2092)
Wafer clean inspect	Single machine
Wafer packaging	Assembly machine
Wire saw operator	Labor
Wafer handler	Labor

Conceptual model design of the wire saw area and the wafer production is shown in Table 7. A single machine is used to pull the good bricks from the good bricks buffer and push it to the block set input buffer in zero time. The assemble block set machine is a multi-cycle machine which pulls 16 bricks at a time from the input buffer and assembles them into four brick mounts (each mount containing 4 bricks) which is considered a block set and pushes it to the block set output buffer which has a capacity of 3 block sets. The wire saw is a multi-cycle machine which pulls a block set and saws it. Wire saw machine breakdown has been modeled on busy time with a negative exponential time distribution with a mean of 2000 hours and the block set is pushed to scrap after the breakdown related repair is complete. Preventive maintenance is done as per the schedule before loading a block set every 175 hours. After the wire saw completes its cycle, the solvent tank, which is a multi-cycle machine, pulls the block set from wire saw machine and retains it for 7.2 hours. To model the workers pulling block mounts from the solvent tank if the central buffer is empty, a general machine is used which changes each block set to four block mounts. A zero-time multicycle machine is used to convert a block mount to 2092 wafers and store it in an individual wafer buffer because each block set has 4 block mounts, and each block set gives 8369 wafers. The wafer separation, cleaning and inspection machine which is modeled as a multi-cycle machine pulls a wafer from individual wafer buffer and pushes good wafers to the packaging machine and scraps bad wafers with a probability of 90.66% and 9.34% respectively. The wafer packaging machine is an assembly machine which waits till it receives 100 good wafers from wafer clean inspect machine and packs them to create a wafer stack box with 100 wafers and ships it to inventory.

Answers to specific questions from grading template:

a) Grade A – Each entity was modeled as a half Kg and the entity was made active with a lot size of 1600 and inter arrival time equal to 10^{20} to ensure that at time T = 0, 1600 entities of grade A material are filled in the grade A buffer only once during the entire simulation run.

   The remaining entities in my model are Grade B, By product, 680Kg/4000Kg Crucibles, 680Kg/4000Kg Sealed Crucibles, 680Kg/4000Kg Baked Crucibles, 680Kg/4000Kg Filled Crucibles, Purified Ingot, Production Ingot, Chunks, Bricks, Block set, Block Mount, Wafer and Wafer stack box. All these entities are made passive.

b) In the crucible prep process, if the baked crucible buffers end up getting full and the oven has one of the crucibles in it, it creates a dead lock. To manage this, an if condition for pull rule was used in the oven as shown in Figure 4. As per the rule, if the 680Kg baked crucible buffer has less than 2 crucibles in it, then 680Kg sealed crucibles are pulled. Else if there are no crucibles in the 400 Kg baked crucible buffer, 400 Kg sealed crucibles are pulled. Additionally, sealed crucible buffers are not allowed to have more than one crucible at any time to ensure the crucibles are pulled only when needed as shown in Figure 3.

Edit INPUT RULE FOR MACHINE Paint_Booth

Select Search Editor Print

```
IF NParts (Sealed_680Kg_Buffer) <= 1
 PULL from Crucible_680Kg out of WORLD
ELSE
 IF NParts (Sealed_400Kg_Buffer) <= 1
  PULL from Crucible_400Kg out of WORLD
 ENDIF
ENDIF
```

Figure 3 Pull rule for crucibles into paint booth

Edit INPUT RULE FOR MACHINE Crucible_Bake_Oven

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```
IF NParts (Baked_680Kg_Buffer) < 2
 PULL from Sealed_680Kg_Buffer
ELSEIF NParts (Baked_400Kg_Buffer) = 0
 PULL from Sealed_400Kg_Buffer
ELSE
 Wait
ENDIF
```

Figure 4 Pull rule for crucibles into the oven

c) In the crucible fill station, if the Grade_A buffer goes below 900, which is enough material to fill one production crucible and some extra, a 680 Kg baked crucible is pulled as seen in Figure 5. This will ensure that a purification ingot is produced to refill Grade A buffer.

Edit INPUT RULE FOR MACHINE Crucible_Fill CYCLE 1

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```
IF NParts (Grade_A_Buffer) <= 900
 PULL from Baked_680Kg_Crucible out of Baked_680Kg_Buffer
ELSE
 PULL from Baked_400Kg_Crucible out of Baked_400Kg_Buffer
ENDIF
```

Figure 5 Pull rule for crucible fill station

d) The facility has a target of producing 1.8 Megawatt per month. Below is the process to calculate the number of crucibles that need to be processed to achieve this target. This information can be used to validate if the simulation is producing the ingots in correct ratio and the target quantities of other entities in the simulation.

i. One wafer produces 4.13 watts of energy. To calculate the number of good wafers that are needed per month to produce 1.8 MW is as follows:

$$\#\ of\ good\ wafer\ per\ month = \frac{1.8 * 10^6}{4.13} = 435{,}836$$

ii. As each block set from wire saw produces 8369 wafers out of which only 90.66% are good, it implies we have 7587 (8369*0.9066) good wafers from one block set.

Therefore, to calculate the number of block sets needed per month will be:

$$\#\ of\ Block\ sets\ per\ month = \frac{435836}{7587} = 57.4415 \sim 58$$

iii. As each block set has 16 good bricks, the number of good bricks needed per month are:

$$\#\ of good\ bricks\ per\ month = 57.4451 * 16 = 919.1216 \sim 920$$

iv. Each block set needs 16 good bricks which are derived from a production ingot. As each production ingot produces 144 bricks out of which only 91% are good, the good bricks produced are only 131 (144*0.91). The number of production ingots or production crucibles that need to be processed per month will be:

$$\#\ of\ Prod. Ingots\ per\ month = \frac{919.1216}{131} = 7.0162 \sim 7$$

v. Each production ingot needs 400 Kg of grade A material. Each purified ingot needs 80 Kg of grade A material. As the source of grade A material is a purified ingot which weighs 680 Kg and 37% of the chunks of a purified ingot are grade A, each purified ingot produces 251.6 Kg (680*0.37) of grade A material. To calculate the number of purification ingots that need to be processed to produce one production ingot, need to set up an equation where 'x' is the number of purification ingots

$$400 + 80 * x = 251.6 * x$$

$$x = \frac{400}{251.6 - 80} = 2.33102$$

This implies we need to produce 2.331 purification ingots $i.e.,$ the ratio of purific ations ingots to the production ingots is 2.331. To calculate the number of purification ingots or crucibles per month required to achieve the target of 1.8 MW of energy per month

$$\#\ of\ Purification\ Ingots\ per\ month = 7 * 2.331 = 16.317 \sim 16$$

vi. The number of productive furnace hours depends on the total number of production and purification ingots that need to be processed in a month. As we know that a production crucible takes 90 hours, and a purification crucible takes 50 hours

$$\#\ Productive\ furnace\ hrs. per\ month = 7 * 90 + 16 * 50 = 1430\ Hrs.$$

e) Please refer to Table 7 and its description

f) The quantities of raw material and the corresponding parts that are produced are shown in Figure 6. Each Grade A, Grade B, Raw clean ore, chunks and by product entity represents half kg of material in real life. Therefore, each purification ingot consumes one crucible, 160 Grade A, 1200 Grade B (or Raw clean ore if Grade B entities are not available in buffer). Similarly, each production ingot consumes 800 Grade A entities.

Each purification ingot is crushed into 1360 chunks because each chunk entity represents half kg material. Then 37% (503) of the chunk entities end up in Grade A buffer, 46% (626) of the chunk entities end up in Grade B buffer and 17% (231) of the chunk entities end up in by product buffer.

Each production ingot produces 144 bricks out of which 91% (131) are good bricks and 9% (13) bad bricks. The 131 good bricks give 8 block sets (131/4) which give 32 block mounts (8*4). 32 block mounts give 66944 wafers of which 60691 are good wafers and 6253 are bad wafers and are scrapped. The 60691 good wafers produce 606 wafer stacks (60691/100). Each brick is 2.5 Kg which is equal to 5 Grade A entities. Therefore 13 bad bricks are converted to 65 (13*5) Grade A entities and sent to Grade A buffer.

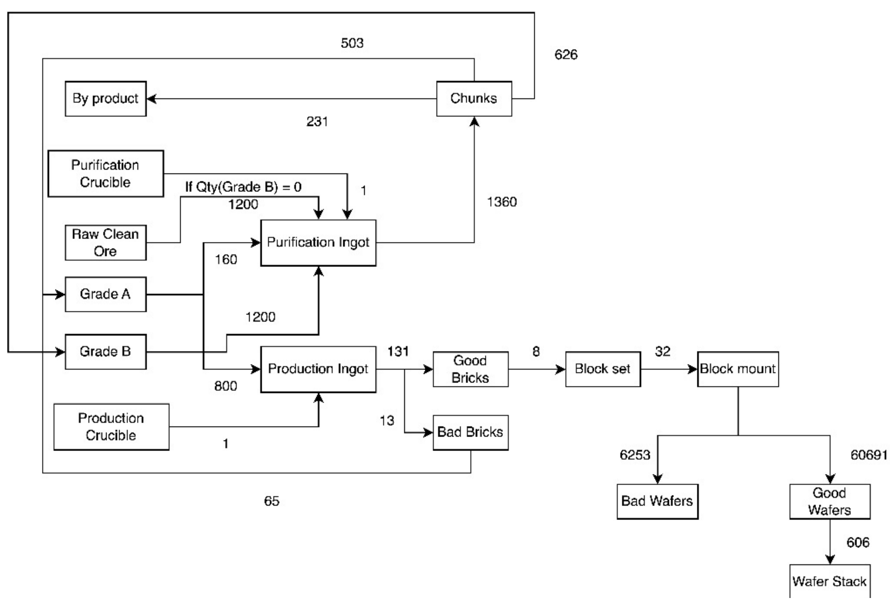

Figure 6 Change in the quantities of entities

Preliminary Experimental Design

The goal of this study is to build a discrete event simulation model of a pilot facility that makes solar cells as described in the previous sections and then add resources over 12 months (maximum of $ 0.5 million can be spent each month) to expand the facility and produce enough wafers each month that can generate 1.8 Megawatts of energy. To achieve this, the performance metrics of the plant must be established prior to planning its expansion.

Below are the performance metrics of the plant that will be collected in every simulation run:

1) Number of wafer stacks per year
2) Number of wafers per month
3) Watts per month
4) Cost per wafer
5) Investment in the specific month
6) Resources added in the specific month

There are multiple resources like the number of machines and the number of operators in an area (Brick production, Wafer production & Ingot production etc.) that can be added to the plant each month. However, a good combination must be found, and this can be done in two ways i.e., by conducting a traditional design of experiments or by identifying bottlenecks and adding resources to the bottleneck. In this project, the best combination of resources will be found using the bottleneck approach as it is easier and less computationally intensive. This method will be discussed further in the final experimental design section.

Input Data Preperation

The data for the project was provided by Dr. Huff. However, if this project was to be conducted in real world, the following data would be needed:

- The cycle times associated with labor handling production ingots, moving crushed purified ingot chunks to the respective bins after sorting, sealing of crucibles, filling crucibles and cleanup of the crucibles after they shatter in the cooling stand has been deterministic in the current model. This is not true in real life and hence, data on these cycle times needs to be collected and an appropriate distribution needs to be fitted and used in the model.
- If the operators move from one location to another (ore cleaning to purified ingot crushing), the time to move has not been considered in the current model. Therefore, the move time could possibly be used.
- Wire saw breakdown repair times are deterministic and this is not realistic as the repair times are stochastic. Therefore, repair time needs to be modeled as per the appropriate distribution based on machine data.
- Production ingot dicing saw does not have breakdowns scheduled in the current model. This information needs to be collected about the machine and use appropriate distribution to model breakdown intervals.
- When the production ingot is diced, some material is left over, and this can be recycled. This information is not available and is not included in the current model. If the weight of material left over from each production ingot after it is diced is known, it can be sent back to grade A buffer and modeled appropriately.

Model Translation

Below are the screen shots of the Witness base model.

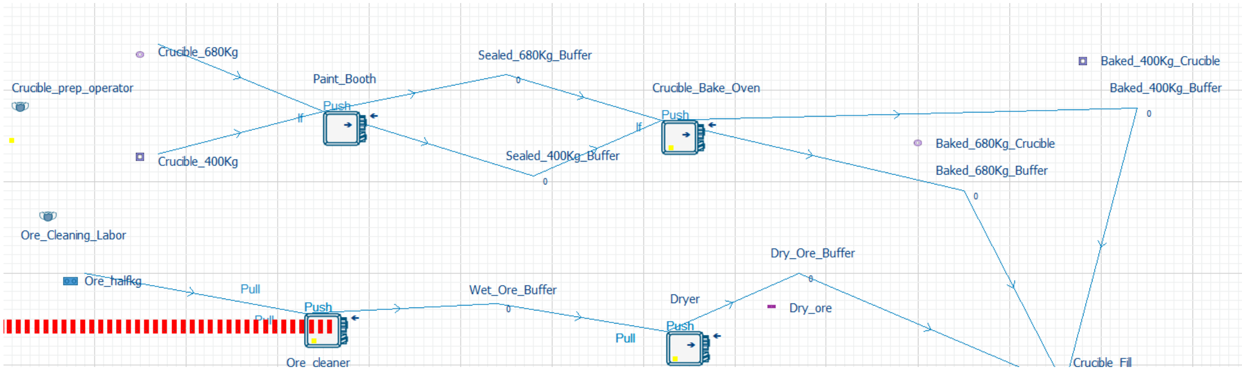

Figure 7 Crucible prep and ore cleaning area

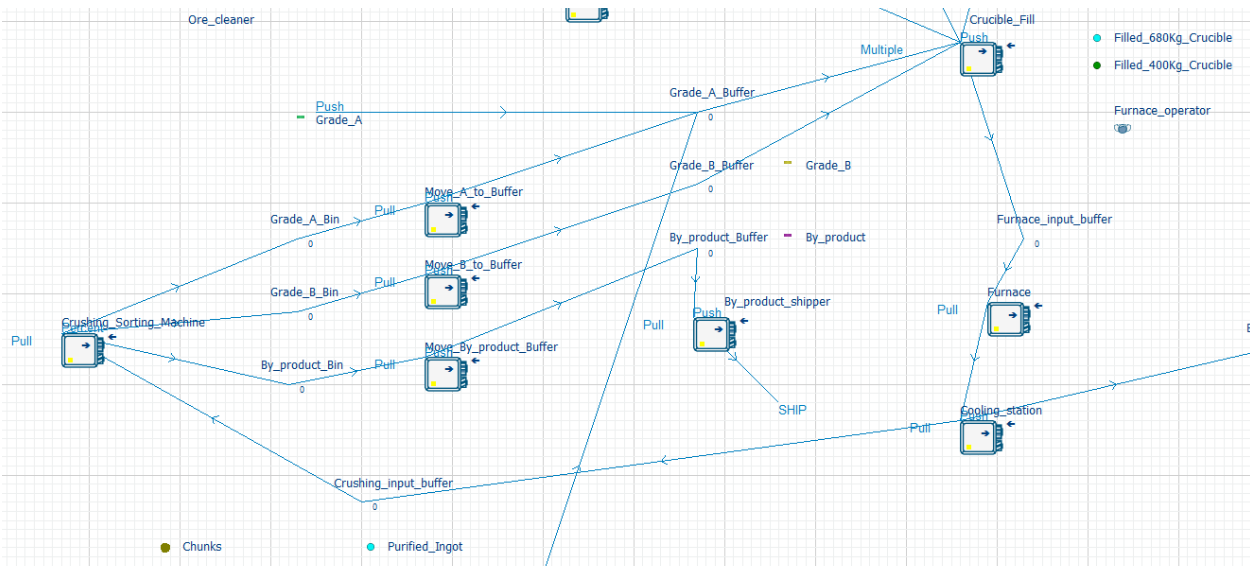

Figure 8 Crucible fill, Furnace and purified ingot crushing area

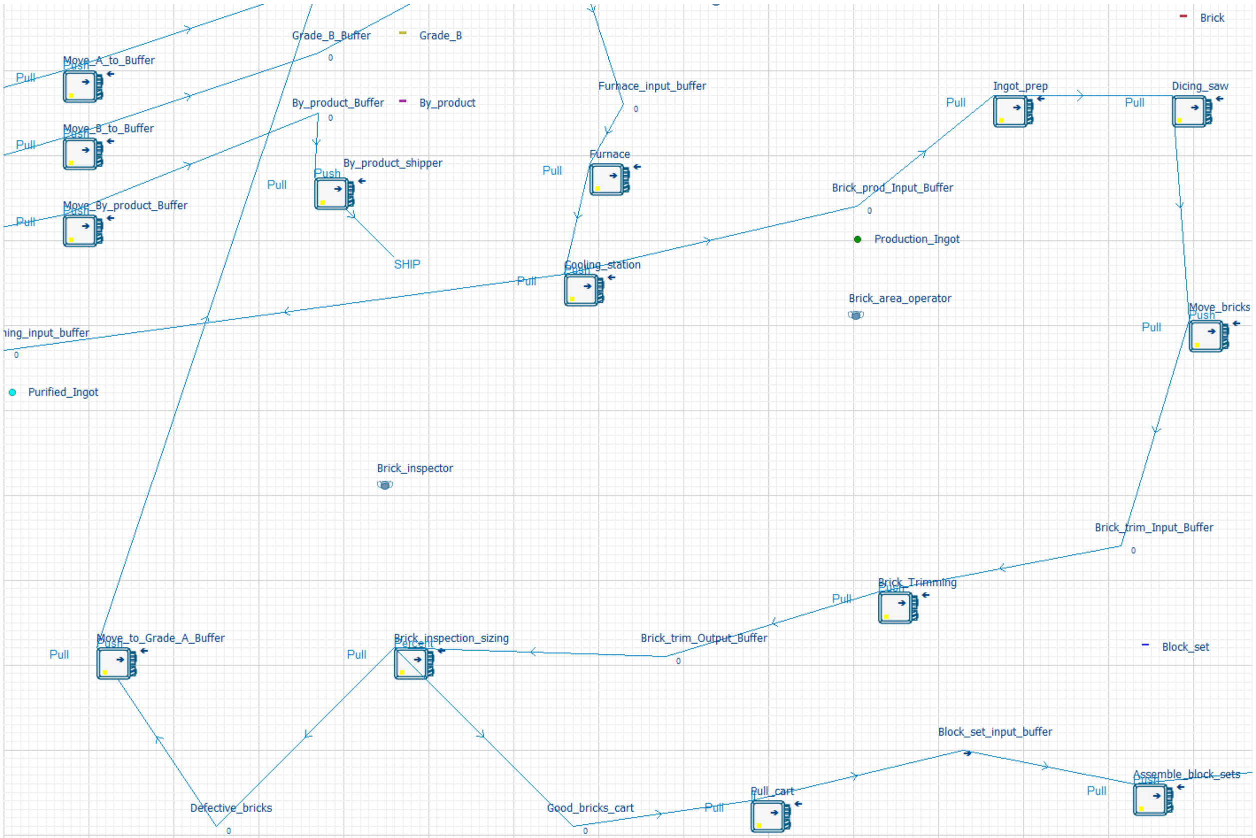

Figure 9 Brick production area

Figure 10 Wire saw and wafer production area

The cost of a wafer in the base model (pilot facility) is $ 4.73 per unit. The pilot plant is at 12.75% of the target monthly capacity.

Model Verification and Validation

In this section, the base model being submitted with this assignment will be compared with a validated model i.e., Dr. Huff's model.

Statistics Report   Report by On Shift Time

Part   Machine   Buffer   Labor   Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	22140	0.000	0.000	19440.000	0.000	2700.000	2706.501	61611.406	6.000
Crucible_400Kg	22	0.000	0.000	20.000	0.000	2.000	2.029	46484.091	6.000
Crucible_680Kg	34	0.000	0.000	32.000	0.000	2.000	2.047	30341.324	6.000
By_product	8500	8400.000	0.000	0.000	0.000	100.000	104.444	6192.928	6.000
Grade_A	19780	0.000	0.000	19200.000	0.000	580.000	608.757	15511.303	6.000
Dry_ore	22080	0.000	0.000	19440.000	0.000	2640.000	2818.484	64334.965	6.000
Grade_B	23300	0.000	0.000	22560.000	0.000	740.000	581.530	12579.011	6.000
Baked_680Kg_Crucible	37	0.000	0.000	35.000	0.000	2.000	3.397	46270.654	6.000
Baked_400Kg_Crucible	21	0.000	0.000	17.000	0.000	4.000	2.706	64952.501	6.000
Filled_680Kg_Crucible	41	0.000	0.000	36.000	0.000	5.000	5.001	61471.865	6.000
Filled_400Kg_Crucible	18	0.000	0.000	16.000	0.000	2.000	2.170	60770.971	6.000
Purified_Ingot	36	0.000	0.000	36.000	0.000	0.000	0.016	226.666	6.000
Brick	2338	0.000	0.000	1582.000	0.000	756.000	767.224	165389.673	6.000
Production_Ingot	16	0.000	0.000	13.000	0.000	3.000	2.264	71327.615	6.000
Block_mount	354	0.000	0.000	351.000	0.000	3.000	1.507	2145.409	6.000
Chunks	48960	0.000	0.000	48960.000	0.000	0.000	0.548	5.646	6.000
Block_set	95	0.000	1.000	88.000	0.000	6.000	5.880	31196.882	3.785
Stacked_Wafer_box	6665	6665.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	737930	0.000	68848.000	666500.000	0.000	2582.000	3179.973	2171.895	2.821

Figure 11 Part counts of the pilot facility (Base model)

<u>*Wafer stacks*</u>:
The number of wafer stacks produced by this model is 6665 as seen in Figure 11 and it is very close to those produced by validated model (Dr. Huff's model). This number was 6677 for this model initially before validation. There were some changes that were made to this model which resulted in the wafer stacks matching the validated model (discussed further).

<u>*Ore, Grade A & crucible consumption*</u>:
As half kg was the weight of the ore entity in this model, converting 22140 to entities weighing 30 Kg as used by the validated model, it equals 369. Therefore, this model uses 5.384% less ore than the validated model.

Each grade A entity in the model is half kg. Therefore, converting 19780 to entities weighing 40 Kg as used by the validated model, it equals 247.25 grade A entities and is 5.662% more than 234 grade A entities that entered the validated model.

This model consumes 36 purification crucibles and 20 production crucibles which is less crucibles compared to the validated model which consumes 35 purification crucibles and 11 production crucibles. The No. Assembled is being compared here.

<u>*Machine Status Chart*</u>**:**

When the solvent tank of this model was checked, it was waiting for labor for more than 15% compared to the validated model. On investigating it was found that the solvent tank was converting block set to block mounts and pushing the mounts to the central buffer by itself using wafer handler. This was not representing reality because the wafer handler is going to pull the mounts from the solvent tank only when the central buffer is empty. When this was changed, the solvent tank was not waiting for labor anymore. After this the wafer clean inspect machine was blocked for more than 20% compared to the validated model. On investigation, it was found that the wafer clean inspect machine was splitting a block mount into 2092 wafers using a percent rule on all the wafers produced with a total cycle time of 244.066 minutes. This is incorrect as the wafer handler is expected to inspect each wafer individually and then determine if it is good or bad with a probability of 90.66% and 9.34% respectively. This was changed to represent the process accurately as described in Table 7 conceptual model design section, the wafer stack numbers got closer to that of the validated model. The machine state chart after making changes is seen in Figure 12.

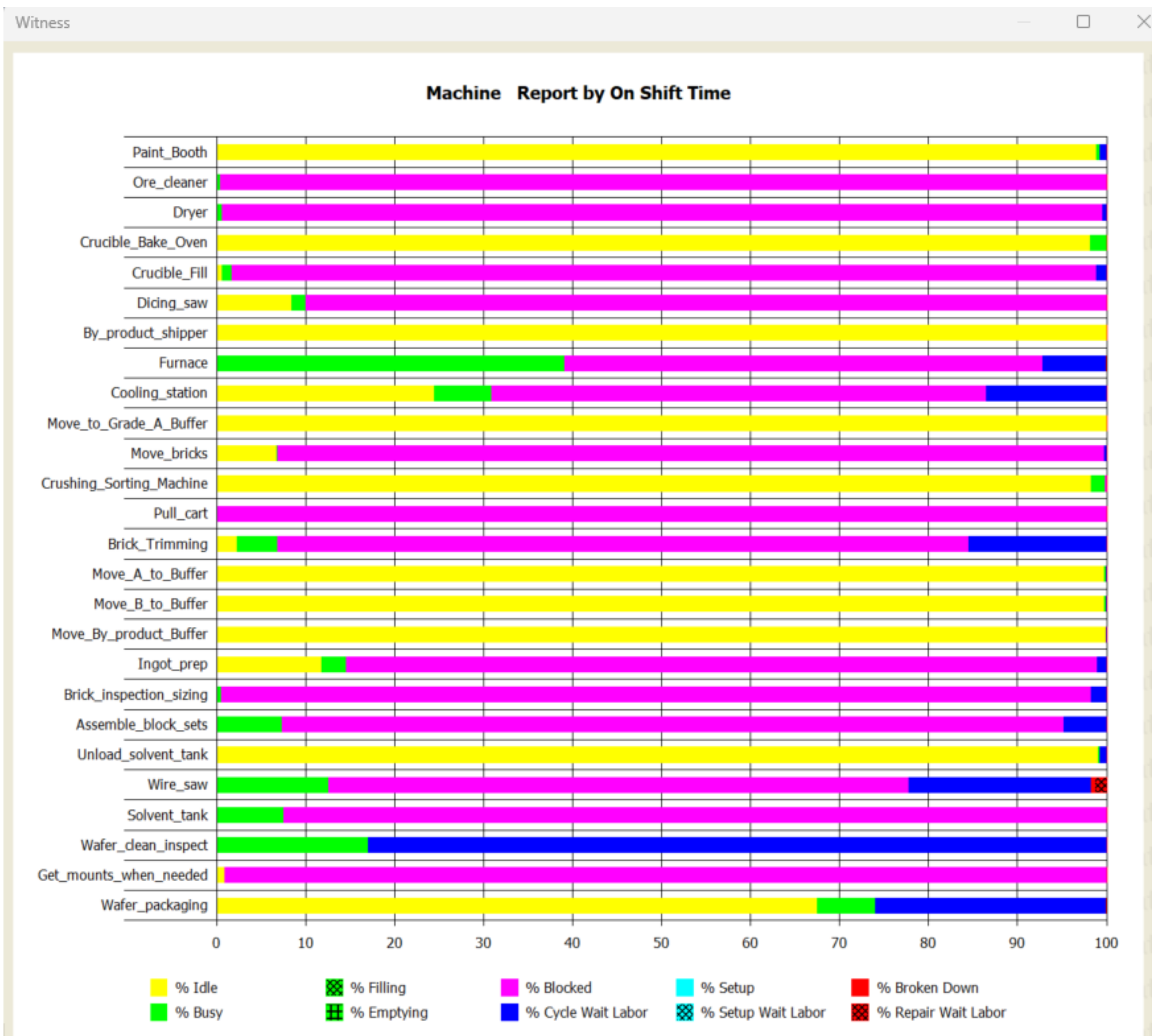

Figure 12 Machine state chart

When the labor utilization chart of this model was compared with the validated model. It was found that the crucible prep operator was underutilized 3%and the furnace area operator was over utilized by 15%. Upon investigation it was found that the furnace area operator was filling crucibles, and this was not right. Furthermore, Ore cleaning operator can do all the tasks that the crucible prep operator can do but not vice versa. When this was changed, the labor utilizations for all the labor in this model matched the validated model as seen in Figure 13. However, the wire saw area operator is utilized more compared to the validated model.

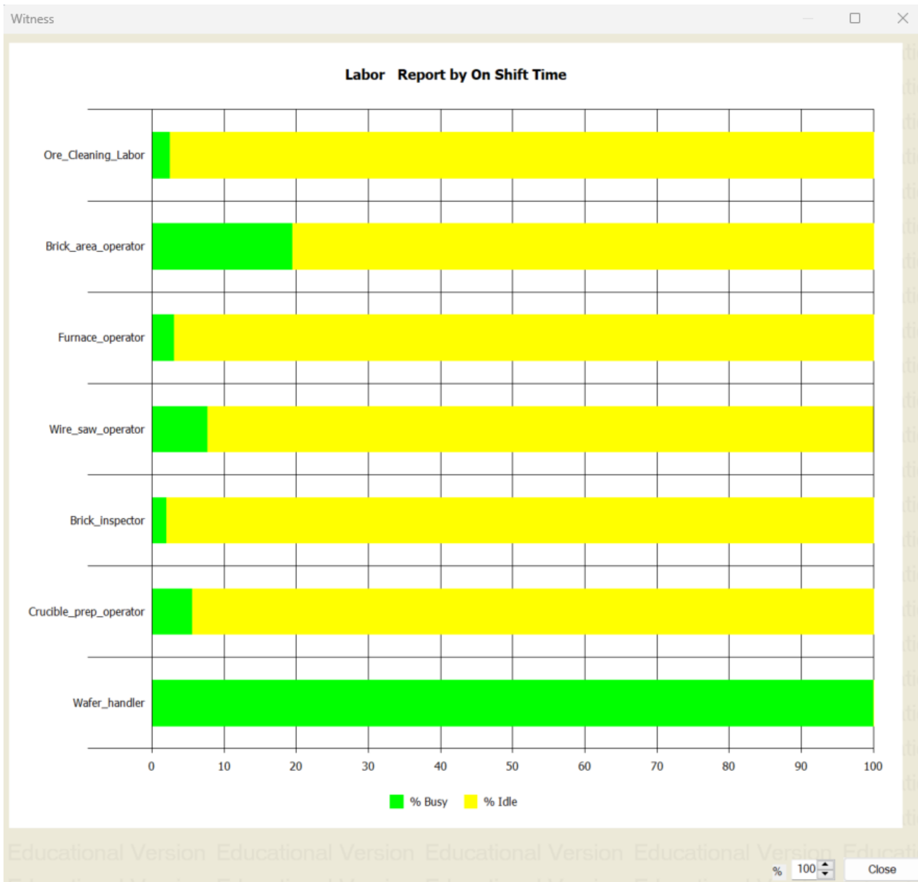

Figure 13 Labor utilization chart

Final Experimental Design

As stated in the preliminary experimental design, there are two ways to conduct experiments. One is to use a design of experiment (DoE) where we will have to consider all the possible values of variables i.e., number of machines, buffers and operators and evaluate the combinations as per the DoE one at a time. However, this can be time consuming and therefore, adding resources by identifying bottlenecks is more efficient.

In the bottleneck approach, multiple resources that can be purchased within $ 0.5 million are selected by identifying bottlenecks. The bottleneck selection and the action to be taken is done as follows:

- A machine is not idle, and is busy for more than 95% of the time and blocked or waiting for labor for the remaining time
    - Add another machine
- A machine is not idle and is mostly waiting for labor and labor on weekday 1st shift is busy 100%
    - Add labor on weekday 1st shift
- A machine is not idle and is mostly waiting for labor and the labor on weekday 1st shift is not busy (*Implies parts are waiting during off shift hours in the area*)
    - Add labor on weekend 1st/2nd shift or on weekday 2nd / 3rd shift

The bottleneck might shift in the same iteration and hence the $0.5 million might have to be invested in multiple locations. If there is an increase in production, the resources added for the month and the corresponding cost per unit will be recorded and the process is repeated until the monthly production target is achieved or the available funds are used up.

To determine if adding resources helped, the monthly production should increase and the price per unit should drop compared to the configuration without the added resource. If the price per unit remains the same, it implies that the production increase compared to the resources added was not significant.

As the facility is to be run for 50 weeks and there are three 8-hour weekday shifts and two 12-hour weekend shifts in 24 hours, the run time should be 504,000 minutes (60 * 24 * 7 * 50). However, production for some period in the beginning is not going to be in a steady state and is likely to keep increasing. An estimate for how long it takes for the plant to reach steady state production is not known and hence to be safe, the first 100,000 minutes of production needs to be considered "Warmup" period and the data needs to be discarded. Therefore, a "Warmup" period of 100,000 is chosen and a run time of 604,000 is chosen so that the data for 504,000 minutes is recorded considering the lost warmup period.

There is no change in what was planned for investigation during the preliminary experimental design and the current stage.

Experimentation, Analysis, and Interpretation

In this section, the results of the experiments will be presented with the rationale for the decisions taken for the respective month.

1st Month

As seen in the results of the base model in the verification and validation section of this report, the wafer cleaning, inspection, and packaging machine is busy 18% of the time and waiting for labor for the remaining time. The labor in this area is busy 100% of the time. The soak time is blocked 92% of the time and busy for the remaining time. The wire saw is not idle and waits for labor 20% of the time.

Hence, the following resources are added in the 1st month costing $ 450,000:

1. Wafer handlers on Weekday 1st shift – 2
2. Wire saw operator on Weekend 1st shift – 1
3. Wafer cleaning, inspection & packaging stations – 2
4. Soak tank – 1

As seen in Figure 14, the production jumps to 20,000 wafer stacks per year which is 38.24% of the monthly target. Each unit of wafer now costs $ 1.76 per unit. Figure 15 shows the state of the machines and Figure 16 shows the state of the state of the labor. $ 50,000 saved and will be used in the next month.

Statistics Report   Report by On Shift Time

Part   Machine   Buffer   Labor   Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	45900	0.000	0.000	43200.000	0.000	2700.000	2735.564	30037.569	6.000
Crucible_400Kg	42	0.000	0.000	40.000	0.000	2.000	2.058	24697.619	6.000
Crucible_680Kg	78	0.000	0.000	76.000	0.000	2.000	2.104	13592.564	6.000
By_product	18283	18240.000	0.000	0.000	0.000	43.000	105.266	2901.831	6.000
Grade_A	42681	0.000	0.000	41920.000	0.000	761.000	781.470	9228.020	6.000
Dry_ore	45840	0.000	0.000	42960.000	0.000	2880.000	2841.077	31236.972	6.000
Grade_B	49531	0.000	0.000	49440.000	0.000	91.000	762.627	7760.072	6.000
Baked_680Kg_Crucible	81	0.000	0.000	77.000	0.000	4.000	3.440	21403.121	6.000
Baked_400Kg_Crucible	41	0.000	0.000	37.000	0.000	4.000	2.466	30312.805	6.000
Filled_680Kg_Crucible	83	0.000	0.000	78.000	0.000	5.000	4.931	29941.050	6.000
Filled_400Kg_Crucible	38	0.000	0.000	35.000	0.000	3.000	2.463	32673.553	6.000
Purified_Ingot	78	0.000	0.000	78.000	0.000	0.000	0.035	226.666	6.000
Brick	5238	0.000	0.000	4729.000	0.000	509.000	326.829	31447.465	6.000
Production_Ingot	35	0.000	0.000	35.000	0.000	0.000	0.110	1580.600	6.000
Block_mount	1055	0.000	0.000	1054.000	0.000	1.000	1.439	687.246	6.000
Chunks	106080	0.000	0.000	106080.000	0.000	0.000	1.224	5.814	6.000
Block_set	271	0.000	1.000	263.000	0.000	7.000	6.640	12348.472	4.177
Stacked_Wafer_box	20000	20000.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	2208567	0.000	205955.000	2000000.000	0.000	2612.000	3275.903	747.568	2.823

Figure 14 Part statistics report for 1st month

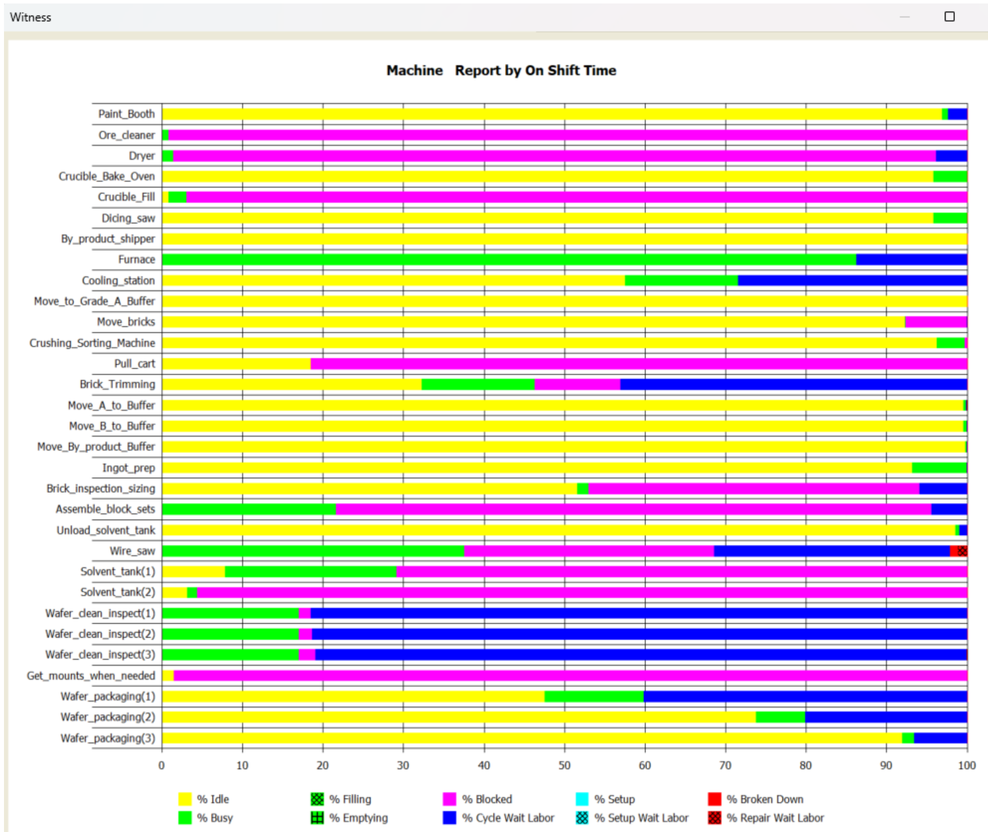

Figure 15 Machine state report for 1st month

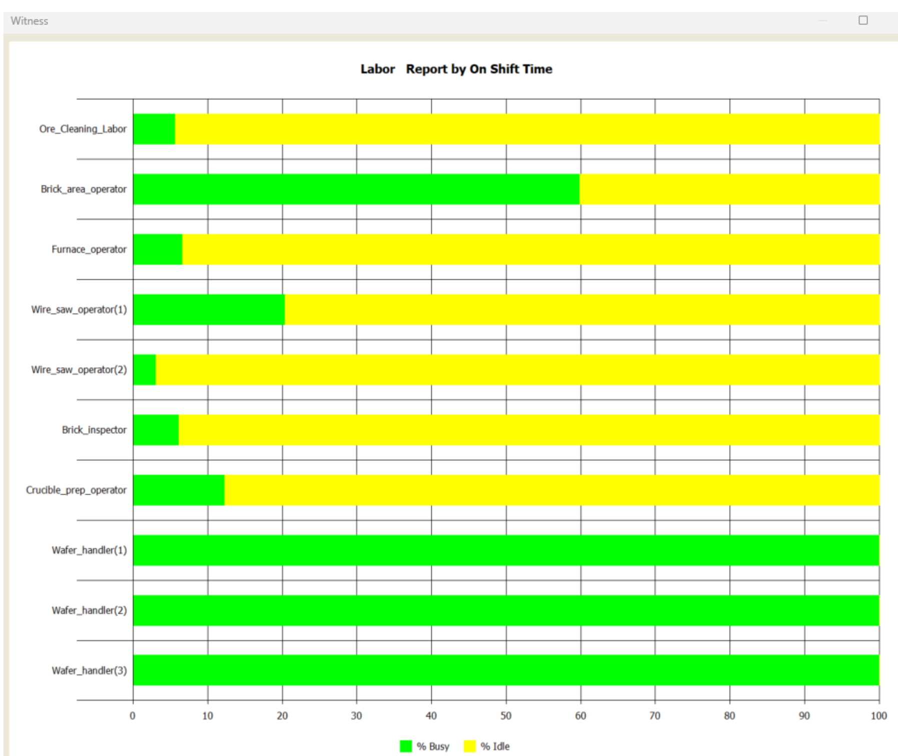

Figure 16 Labor state report for 1st month

2nd Month

As seen in the results of the 1st month in Figure 15, the wafer cleaning, inspection, and packaging machine is busy 18% of the time and waiting for labor for the remaining time. As seen in Figure 16, the wafer handlers in this area are busy 100% of the time.

Hence, the following resources are added in the 2nd month costing $ 100,000:

1. Wafer handlers on Weekday 1st shift – 1

As seen in Figure 17, the production jumps to 22,173 wafer stacks per year which is 42.4% of the monthly target. Each unit of wafer now costs $ 1.63 per unit. Figure 18 shows the state of the machines and Figure 19 shows the state of the state of the labor. Adding one wafer handler has helped and all the wafer handlers are not busy 100% of the time. Furthermore, the wafer cleaning, inspection and packaging and the wire machines are also idle for some time. This indicates that the bottle neck has shifted to some other location (Possibly the furnace).

Cumulative savings of $ 450,000 remain and will be used in the next month.

Statistics Report   Report by On Shift Time

Part   Machine   Buffer   Labor   Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	47340	0.000	0.000	44640.000	0.000	2700.000	2731.659	29082.297	6.000
Crucible_400Kg	42	0.000	0.000	40.000	0.000	2.000	2.058	24697.619	6.000
Crucible_680Kg	78	0.000	0.000	76.000	0.000	2.000	2.096	13543.141	6.000
By_product	18283	18240.000	0.000	0.000	0.000	43.000	104.797	2888.908	6.000
Grade_A	42816	0.000	0.000	41920.000	0.000	896.000	756.348	8903.202	6.000
Dry_ore	47280	0.000	0.000	44160.000	0.000	3120.000	2865.930	30550.526	6.000
Grade_B	49531	0.000	0.000	48240.000	0.000	1291.000	830.748	8453.234	6.000
Baked_680Kg_Crucible	81	0.000	0.000	77.000	0.000	4.000	3.483	21671.010	6.000
Baked_400Kg_Crucible	41	0.000	0.000	37.000	0.000	4.000	2.275	27969.878	6.000
Filled_680Kg_Crucible	83	0.000	0.000	78.000	0.000	5.000	4.923	29896.484	6.000
Filled_400Kg_Crucible	38	0.000	0.000	35.000	0.000	3.000	2.476	32836.184	6.000
Purified_Ingot	78	0.000	0.000	78.000	0.000	0.000	0.035	226.666	6.000
Brick	5158	0.000	0.000	5156.000	0.000	2.000	60.092	5871.727	6.000
Production_Ingot	35	0.000	0.000	35.000	0.000	0.000	0.110	1580.314	6.000
Block_mount	1167	0.000	0.000	1167.000	0.000	0.000	1.446	624.562	6.000
Chunks	106080	0.000	0.000	106080.000	0.000	0.000	1.233	5.856	6.000
Block_set	296	0.000	2.000	291.000	0.000	3.000	3.773	6424.627	3.970
Stacked_Wafer_box	22173	22173.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	2445370	0.000	228044.000	2217300.000	0.000	26.000	2806.031	578.334	2.823

Figure 17 Part statistics report for 2nd month

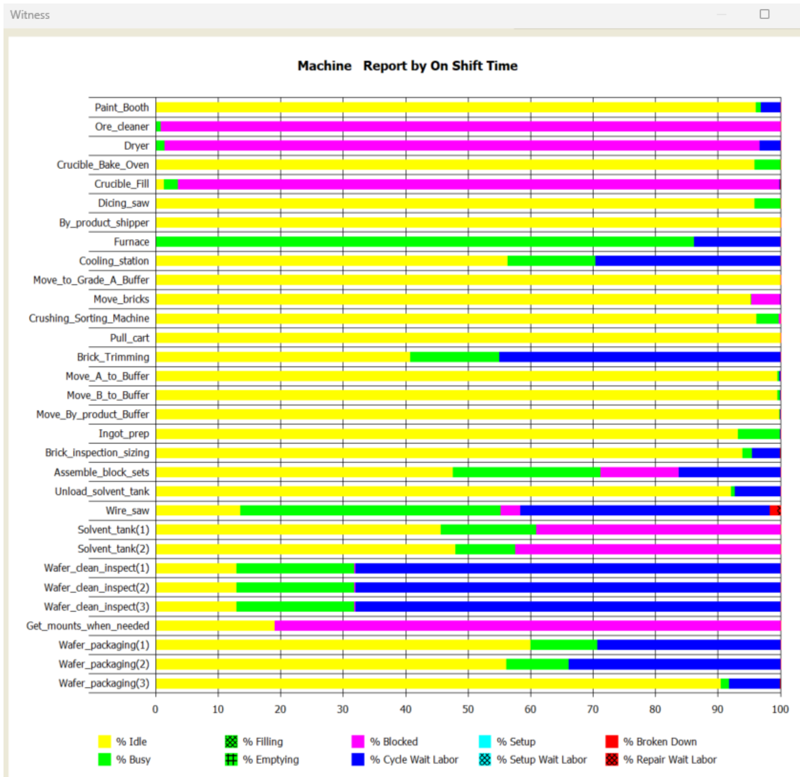

Figure 18 Machine state report for 2nd month

Figure 19 Labor state report for 2nd month

3rd Month

As seen in the results of the 2nd month in Figure 18, the Furnace is busy 85% of the time and waiting for labor for the remaining time. Adding a cooling stand could also help as each furnace would have its own cooling stand. Furthermore, there could be benefit in adding wafer handlers on weekend shift because the wire saws are running over the weekend and the wafer inspection machine is still waiting for labor. The solvent tank is also blocked and hence adding a wafer cleaning, inspection & packaging machine could be beneficial after adding a weekend shift for wafer handler.

Hence, the following resources are added in the 3rd month costing $ 800,000:

1. Furnace – 1
2. Cooling stand – 1
3. Wafer cleaning, inspection, and packaging – 1
4. Wafer handlers on Weekend 1st shift – 1

As seen in Figure 20, the number of wafer stacks produced has increased to 26,328 and is 50.34% of the monthly production target. The cost per wafer is now $ 1.52 per unit. Now the furnace is blocked, and the wire saw, and brick trimming stations are not idle as seen in Figure 21 (Figure 18 vs. Figure 21).
Cumulative savings of $ 150,000 remain and will be used in the next month.

Statistics Report Report by On Shift Time

Part Machine Buffer Labor Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	63180	0.000	0.000	60480.000	0.000	2700.000	2723.497	21725.902	6.000
Crucible_400Kg	50	0.000	0.000	48.000	0.000	2.000	2.068	20844.000	6.000
Crucible_680Kg	106	0.000	0.000	104.000	0.000	2.000	2.155	10248.113	6.000
By_product	23838	23760.000	0.000	0.000	0.000	78.000	115.054	2432.551	6.000
Grade_A	55036	0.000	0.000	54080.000	0.000	956.000	816.639	7478.485	6.000
Dry_ore	63120	0.000	0.000	60000.000	0.000	3120.000	2860.009	22836.570	6.000
Grade_B	65471	0.000	0.000	64800.000	0.000	671.000	763.255	5875.588	6.000
Baked_680Kg_Crucible	108	0.000	0.000	104.000	0.000	4.000	3.365	15705.306	6.000
Baked_400Kg_Crucible	49	0.000	0.000	47.000	0.000	2.000	2.553	26254.510	6.000
Filled_680Kg_Crucible	108	0.000	0.000	103.000	0.000	5.000	5.795	27041.799	6.000
Filled_400Kg_Crucible	52	0.000	0.000	48.000	0.000	4.000	2.728	26441.212	6.000
Purified_Ingot	103	0.000	0.000	103.000	0.000	0.000	0.047	228.770	6.000
Brick	7000	0.000	0.000	6253.000	0.000	747.000	761.432	54823.101	6.000
Production_Ingot	48	0.000	0.000	45.000	0.000	3.000	3.131	32874.979	6.000
Block_mount	1390	0.000	0.000	1388.000	0.000	2.000	1.411	511.618	6.000
Chunks	140080	0.000	0.000	140080.000	0.000	0.000	3.097	11.142	6.000
Block_set	357	0.000	4.000	347.000	0.000	6.000	5.316	7505.334	3.780
Stacked_Wafer_box	26328	26328.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	2907378	0.000	270973.000	2632800.000	0.000	3605.000	3265.414	566.066	2.823

Figure 20 Part statistics report for 3rd month

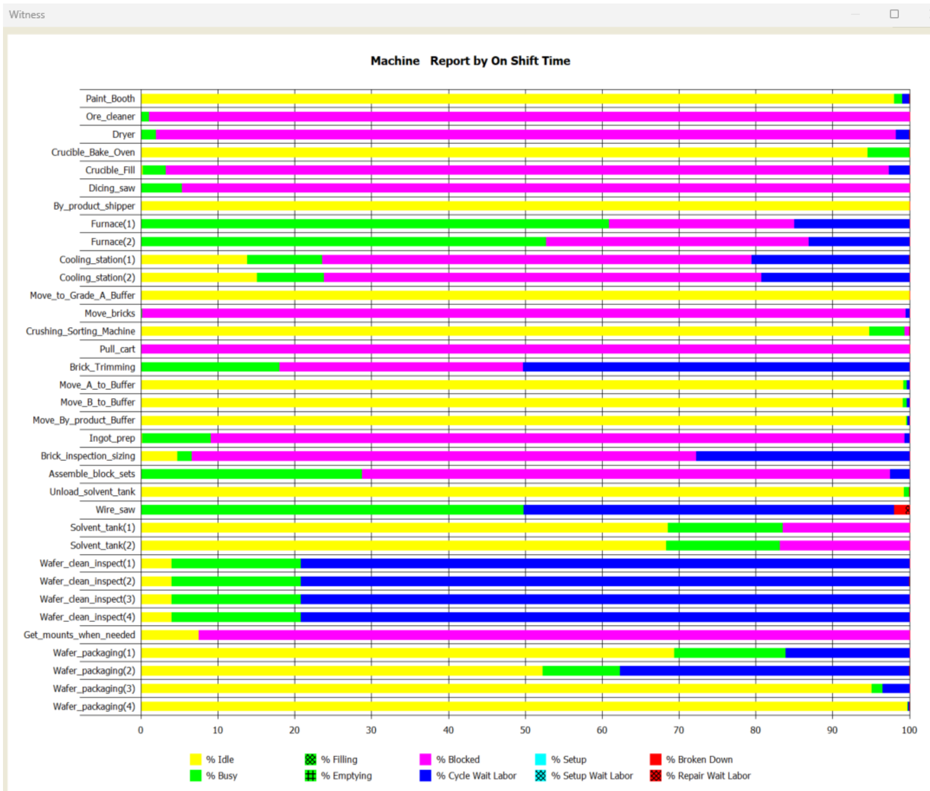

Figure 21 Machine state report for 3rd month

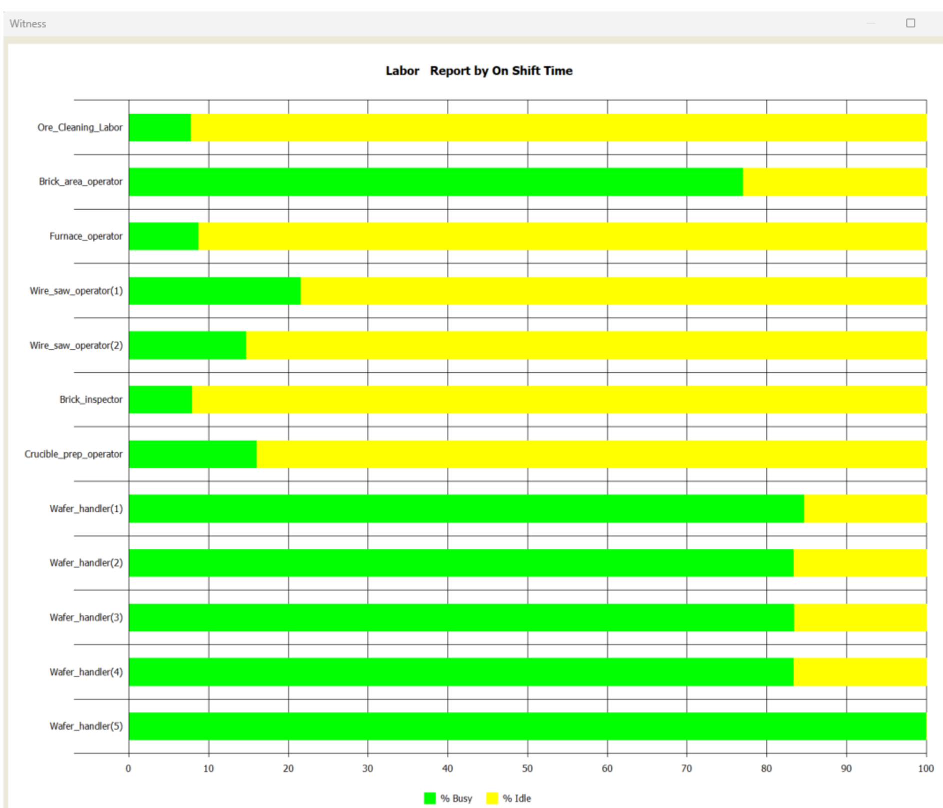

Figure 22 Labor state report for 3rd month

4th Month

As seen in the results of the 3rd month in Figure 21, the wire saw, and brick trimming stations are not idle and possibly the bottleneck. It can also be seen that the wafer handler on weekdays is idle for some time, and the wafer cleaning, inspection and packaging machine is still waiting for labor. Brick trimming stations could also benefit from an operator.

Hence, the following resources are added in the 4th month costing $ 650,000:

1. Wire saw – 1
2. Wafer handlers on Weekday 1st shift – 1
3. Brick trim operator Weekday 1st Shift – 1

As seen in Figure 23, the number of wafer stacks produced has increased to 36,508 and is 69.8% of the monthly production target. The cost per wafer is now $ 1.2 per unit. Now the wire saw is not as busy as it was, and the brick trim station is not blocked.

No savings remain for this month.

Statistics Report   Report by On Shift Time

Part   Machine   Buffer   Labor   Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	80460	0.000	0.000	77760.000	0.000	2700.000	2750.088	17226.502	6.000
Crucible_400Kg	62	0.000	0.000	60.000	0.000	2.000	2.089	16982.419	6.000
Crucible_680Kg	134	0.000	0.000	132.000	0.000	2.000	2.202	8280.709	6.000
By_product	30878	30720.000	0.000	0.000	0.000	158.000	122.912	2006.210	6.000
Grade_A	70878	0.000	0.000	69280.000	0.000	1598.000	857.060	6094.393	6.000
Dry_ore	80400	0.000	0.000	77760.000	0.000	2640.000	2867.102	17972.879	6.000
Grade_B	84329	0.000	0.000	83040.000	0.000	1289.000	857.554	5125.252	6.000
Baked_680Kg_Crucible	136	0.000	0.000	134.000	0.000	2.000	3.453	12796.455	6.000
Baked_400Kg_Crucible	61	0.000	0.000	60.000	0.000	1.000	2.404	19864.672	6.000
Filled_680Kg_Crucible	138	0.000	0.000	133.000	0.000	5.000	5.750	21001.059	6.000
Filled_400Kg_Crucible	65	0.000	0.000	62.000	0.000	3.000	2.825	21906.785	6.000
Purified_Ingot	133	0.000	0.000	133.000	0.000	0.000	0.062	233.483	6.000
Brick	8999	0.000	0.000	8568.000	0.000	431.000	378.047	21173.003	6.000
Production_Ingot	62	0.000	0.000	60.000	0.000	2.000	2.736	22244.419	6.000
Block_mount	1925	0.000	0.000	1925.000	0.000	0.000	1.287	336.841	6.000
Chunks	180880	0.000	0.000	180880.000	0.000	0.000	7.095	19.770	6.000
Block_set	489	0.000	2.000	481.000	0.000	6.000	4.140	4267.413	4.144
Stacked_Wafer_box	36508	36508.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	4030894	0.000	375926.000	3650800.000	0.000	4168.000	3227.030	403.489	2.823

Figure 23 Part statistics report for the 4th month

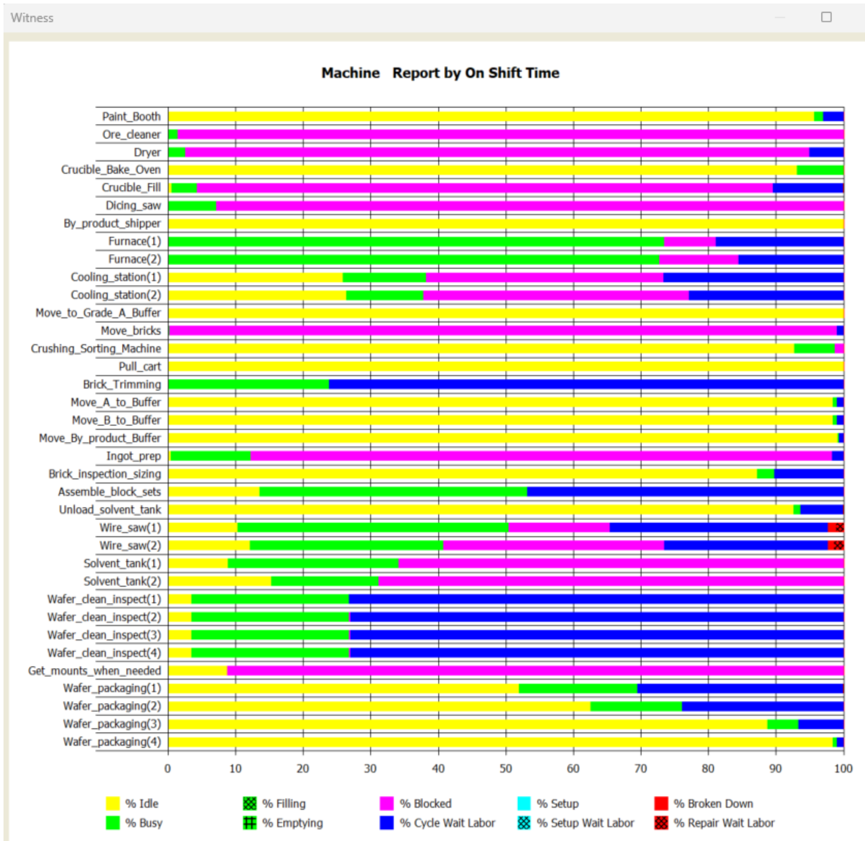

Figure 24 Machine state report for 4th month

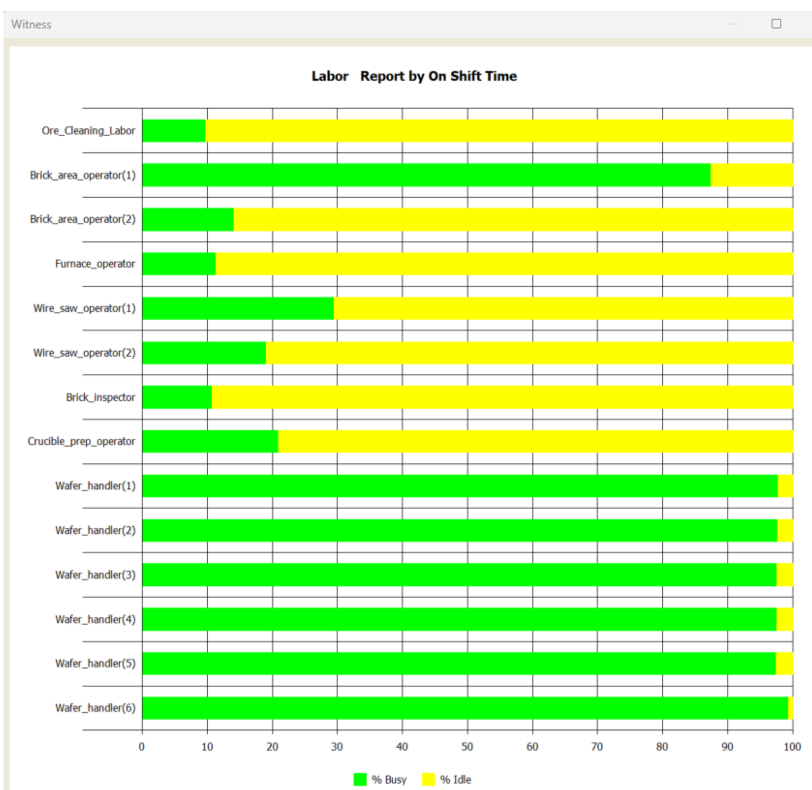

Figure 25 Labor state report for 4th month

5th Month

As seen in the results of the 4th month in Figure 24, and brick trimming stations are not idle and possibly the bottleneck. The solvent tank is blocked for some time and the wafer handlers on the 2nd shift could be helpful.

Hence, the following resources are added in the 5th month costing $ 250,000:

1. Brick trim station – 1
2. Wafer cleaning, inspection, and packaging – 1
3. Wafer handlers on Weekday 2nd Shift – 1

As seen in Figure 26, the number of wafer stacks produced has increased to 42,137 and is 80.57% of the monthly production target. The cost per wafer is now $ 1.08 per unit. The brick mount assembly station is not idle like it was in 4th month (Figure 24 vs. Figure 27).

Cumulative savings of $250,000 remain for this month.

Statistics Report Report by On Shift Time

Part Machine Buffer Labor Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	94860	0.000	0.000	92160.000	0.000	2700.000	2794.771	14848.880	6.000
Crucible_400Kg	74	0.000	0.000	72.000	0.000	2.000	2.105	14334.324	6.000
Crucible_680Kg	162	0.000	0.000	160.000	0.000	2.000	2.234	6949.753	6.000
By_product	36452	36240.000	0.000	0.000	0.000	212.000	125.243	1731.655	6.000
Grade_A	83656	0.000	0.000	82880.000	0.000	776.000	724.684	4365.981	6.000
Dry_ore	94800	0.000	0.000	92160.000	0.000	2640.000	2846.537	15133.490	6.000
Grade_B	99482	0.000	0.000	98640.000	0.000	842.000	941.338	4769.048	6.000
Baked_680Kg_Crucible	164	0.000	0.000	159.000	0.000	5.000	3.365	10342.081	6.000
Baked_400Kg_Crucible	73	0.000	0.000	72.000	0.000	1.000	2.331	16094.817	6.000
Filled_680Kg_Crucible	163	0.000	0.000	157.000	0.000	6.000	5.650	17471.280	6.000
Filled_400Kg_Crucible	77	0.000	0.000	75.000	0.000	2.000	3.029	19823.874	6.000
Purified_Ingot	157	0.000	0.000	157.000	0.000	0.000	0.079	254.023	6.000
Brick	10680	0.000	0.000	9941.000	0.000	739.000	498.681	23533.272	6.000
Production_Ingot	75	0.000	0.000	73.000	0.000	2.000	0.337	2263.712	6.000
Block_mount	2223	0.000	0.000	2222.000	0.000	1.000	1.349	305.882	6.000
Chunks	213520	0.000	0.000	213520.000	0.000	0.000	25.392	59.936	6.000
Block_set	566	0.000	6.000	555.000	0.000	5.000	4.740	4220.785	3.805
Stacked_Wafer_box	42137	42137.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	4651233	0.000	433962.000	4213700.000	0.000	3571.000	3259.517	353.196	2.823

Figure 26 Part statistics report for 5th month

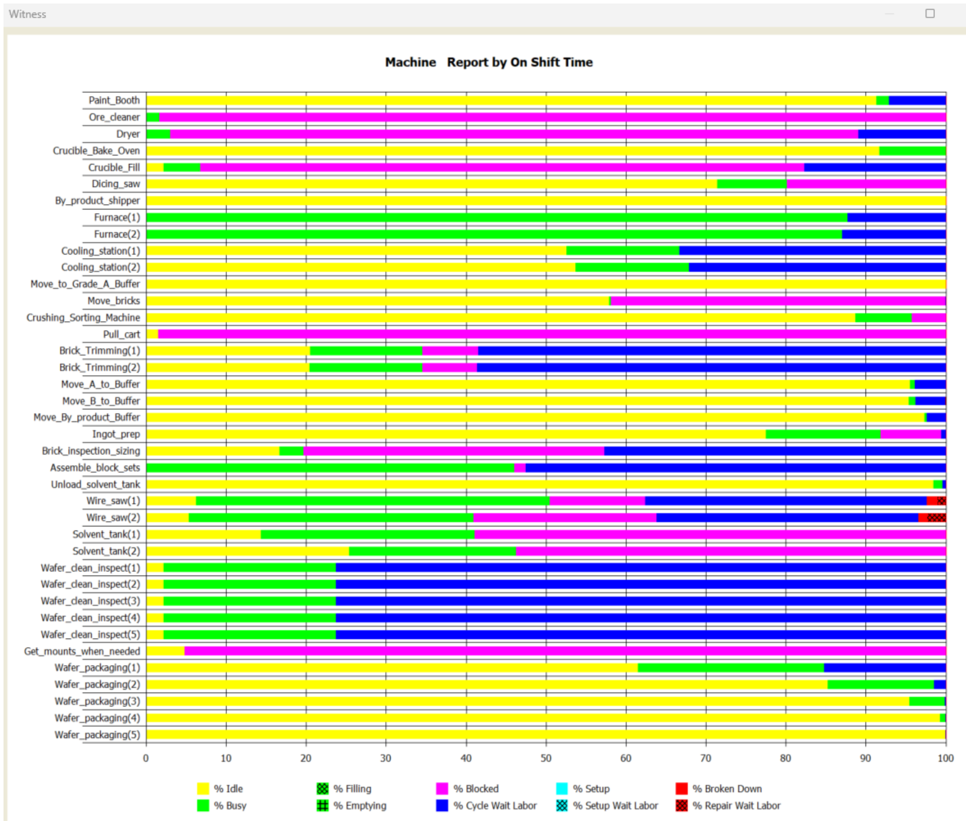

Figure 27 Machine state report for 5th month

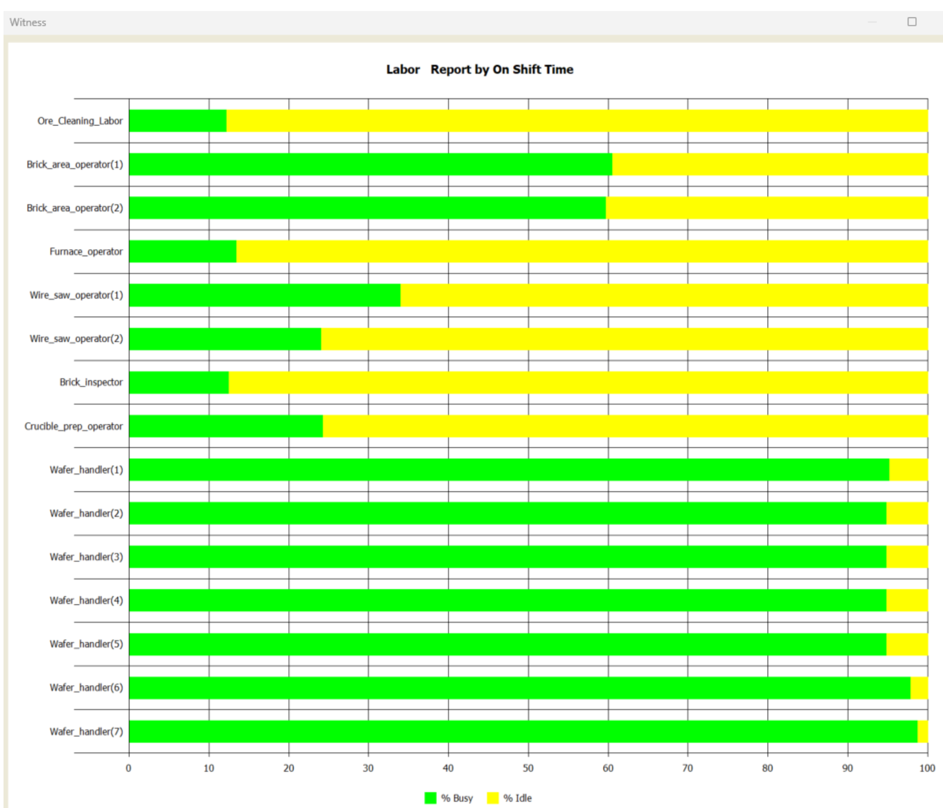

Figure 28 Labor state report for 5th month

6th Month

As seen in the results of the 5th month in Figure 27, the assembly block set machine and the wafer handlers are busier now.

Hence, the following resources are added in the 6th month costing $ 200,000:

1. Assemble block set – 1
2. Wafer handlers on Weekday 1st Shift – 1

As seen in Figure 29, the number of wafer stacks produced has increased to 44,762 and is 85.59% of the monthly production target. The cost per wafer is now $ 1.04 per unit. The assemble block mount machine is not as busy as it was in 5th month (Figure 27 vs. Figure 30).

Cumulative savings of $550,000 remain for this month.

Statistics Report Report by On Shift Time

Part Machine Buffer Labor Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	94860	0.000	0.000	91440.000	0.000	3420.000	2780.148	14771.182	6.000
Crucible_400Kg	74	0.000	0.000	72.000	0.000	2.000	2.097	14282.432	6.000
Crucible_680Kg	160	0.000	0.000	156.000	0.000	4.000	2.256	7105.396	6.000
By_product	36238	36000.000	0.000	0.000	0.000	238.000	130.681	1817.513	6.000
Grade_A	83399	0.000	0.000	82880.000	0.000	519.000	724.617	4379.031	6.000
Dry_ore	94080	0.000	0.000	91200.000	0.000	2880.000	2849.328	15264.258	6.000
Grade_B	98863	0.000	0.000	98400.000	0.000	463.000	960.536	4896.779	6.000
Baked_680Kg_Crucible	160	0.000	0.000	158.000	0.000	2.000	3.348	10546.788	6.000
Baked_400Kg_Crucible	73	0.000	0.000	72.000	0.000	1.000	2.441	16851.507	6.000
Filled_680Kg_Crucible	162	0.000	0.000	156.000	0.000	6.000	5.682	17676.670	6.000
Filled_400Kg_Crucible	77	0.000	0.000	74.000	0.000	3.000	3.044	19923.377	6.000
Purified_Ingot	156	0.000	0.000	156.000	0.000	0.000	0.080	258.429	6.000
Brick	10711	0.000	0.000	10555.000	0.000	156.000	163.644	7700.195	6.000
Production_Ingot	74	0.000	0.000	74.000	0.000	0.000	0.243	1655.257	6.000
Block_mount	2361	0.000	0.000	2360.000	0.000	1.000	1.298	277.070	6.000
Chunks	212160	0.000	0.000	212160.000	0.000	0.000	28.402	67.470	6.000
Block_set	605	0.000	6.000	590.000	0.000	9.000	7.829	6521.759	3.828
Stacked_Wafer_box	44762	44762.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	4939720	0.000	460979.000	4476200.000	0.000	2541.000	3066.232	312.848	2.823

Figure 29 Part statistics report for 6th month

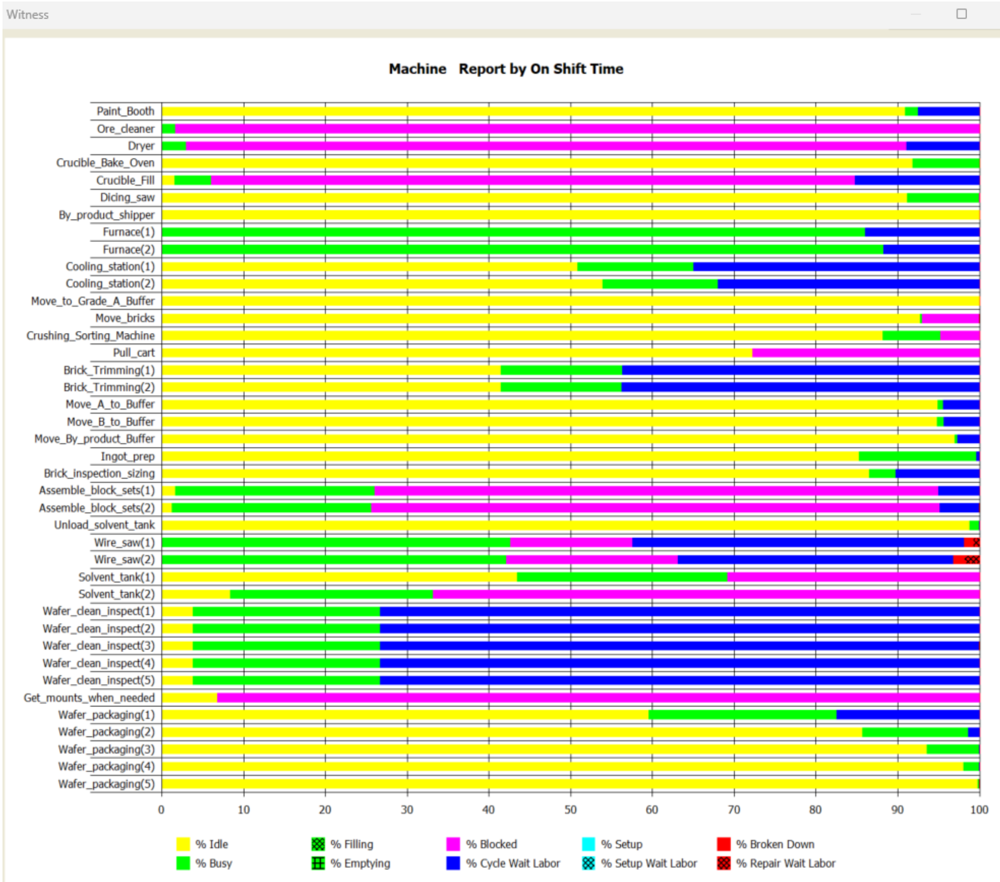

Figure 30 Machine state report for 6th month

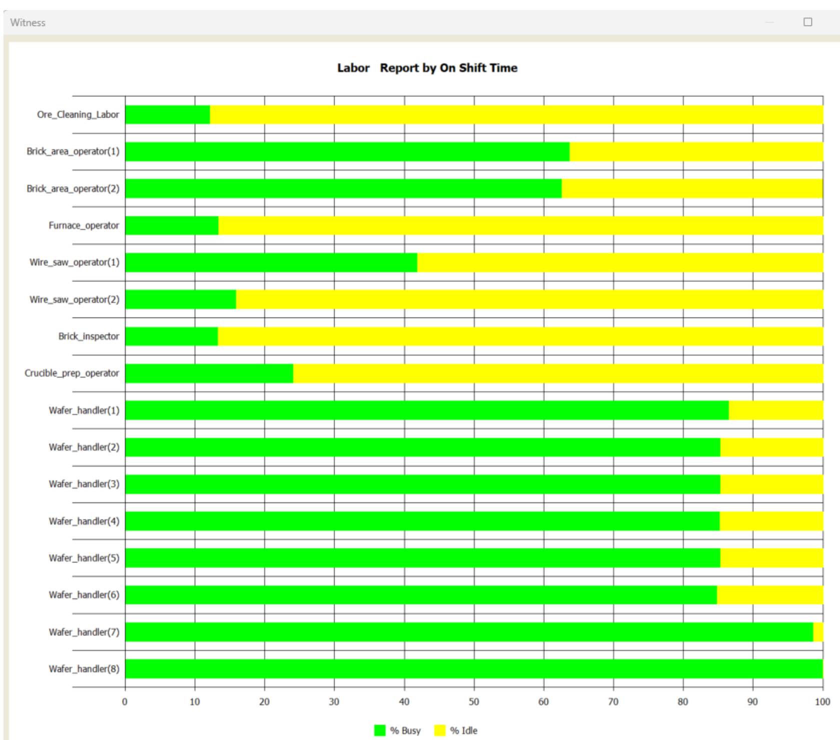

Figure 31 Labor state report for 6th month

7th Month

As seen in the results of the 6th month in Figure 30, both the furnaces are busy. As the wafer cleaning, inspection and packaging machine are waiting for labor, adding a third shift can help.

Hence, the following resources are added in the 7th month costing \$ 1,000,000:

1. Furnace – 1
2. Wire saw operator Weekday 2nd Shift – 1
3. Wafer handler Weekday 2nd Shift – 1
4. Wafer handler Weekday 3rd Shift – 2

As seen in Figure 32, the number of wafer stacks produced has increased to 63,531 and is 121.47% of the monthly production target. The cost per wafer is now \$ 0.84 per unit. Most of the machines beyond the furnace are now idle for some time as seen in Figure 33.

Cumulative savings of \$50,000 remain for this month.

Statistics Report Report by On Shift Time

Part Machine Buffer Labor Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	128700	0.000	0.000	126000.000	0.000	2700.000	2775.966	10870.916	6.000
Crucible_400Kg	105	0.000	0.000	103.000	0.000	2.000	2.188	10502.032	6.000
Crucible_680Kg	223	0.000	0.000	221.000	0.000	2.000	2.343	5295.954	6.000
By_product	52561	52560.000	0.000	0.000	0.000	1.000	142.050	1362.093	6.000
Grade_A	120493	0.000	0.000	118720.000	0.000	1773.000	991.767	4148.380	6.000
Dry_ore	129120	0.000	0.000	126240.000	0.000	2880.000	2815.309	10989.126	6.000
Grade_B	142186	0.000	0.000	140160.000	0.000	2026.000	1061.721	3763.431	6.000
Baked_680Kg_Crucible	224	0.000	0.000	222.000	0.000	2.000	3.037	6832.495	6.000
Baked_400Kg_Crucible	105	0.000	0.000	104.000	0.000	1.000	2.460	11806.429	6.000
Filled_680Kg_Crucible	230	0.000	0.000	225.000	0.000	5.000	6.323	13855.345	6.000
Filled_400Kg_Crucible	106	0.000	0.000	102.000	0.000	4.000	3.471	16505.472	6.000
Purified_Ingot	225	0.000	0.000	225.000	0.000	0.000	0.127	284.214	6.000
Brick	15044	0.000	0.000	14988.000	0.000	56.000	124.924	4185.178	6.000
Production_Ingot	102	0.000	0.000	102.000	0.000	0.000	0.362	1787.471	6.000
Block_mount	3350	0.000	0.000	3350.000	0.000	0.000	1.276	191.955	6.000
Chunks	306000	0.000	0.000	306000.000	0.000	0.000	68.373	112.615	6.000
Block_set	855	0.000	13.000	837.000	0.000	5.000	5.252	3095.779	3.666
Stacked_Wafer_box	63531	63531.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	7012340	0.000	655096.000	6353100.000	0.000	4144.000	3197.697	229.829	2.822

Figure 32 Part statistics report for 7th month

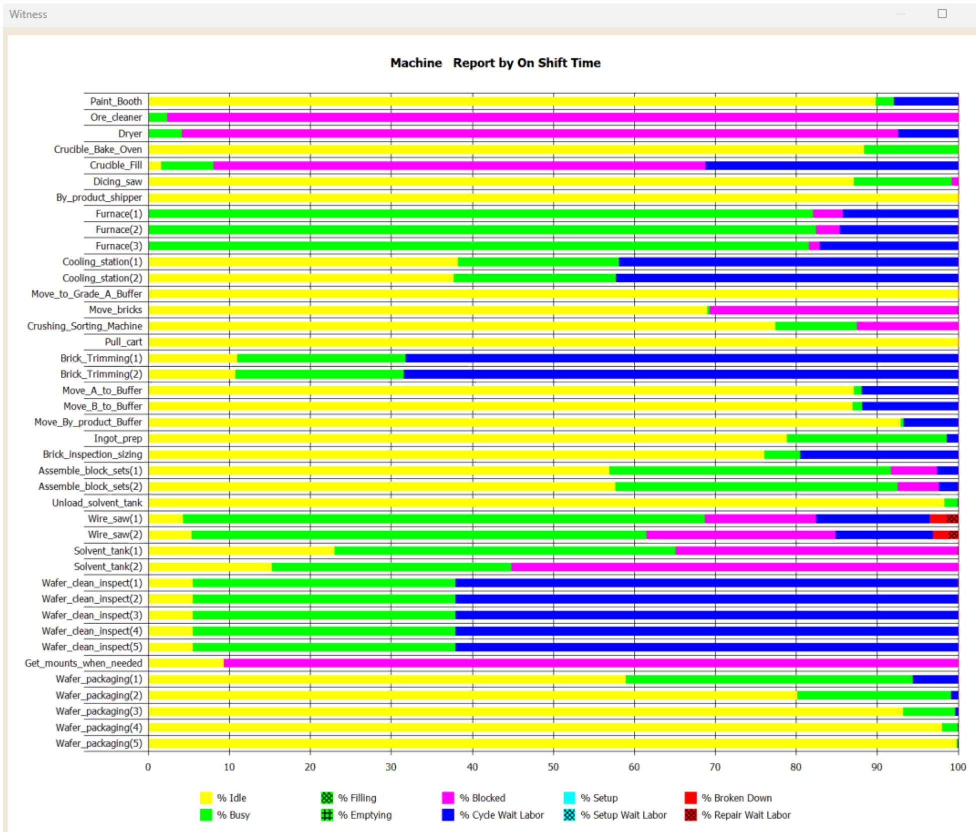

Figure 33 Machine state report for 7th machine

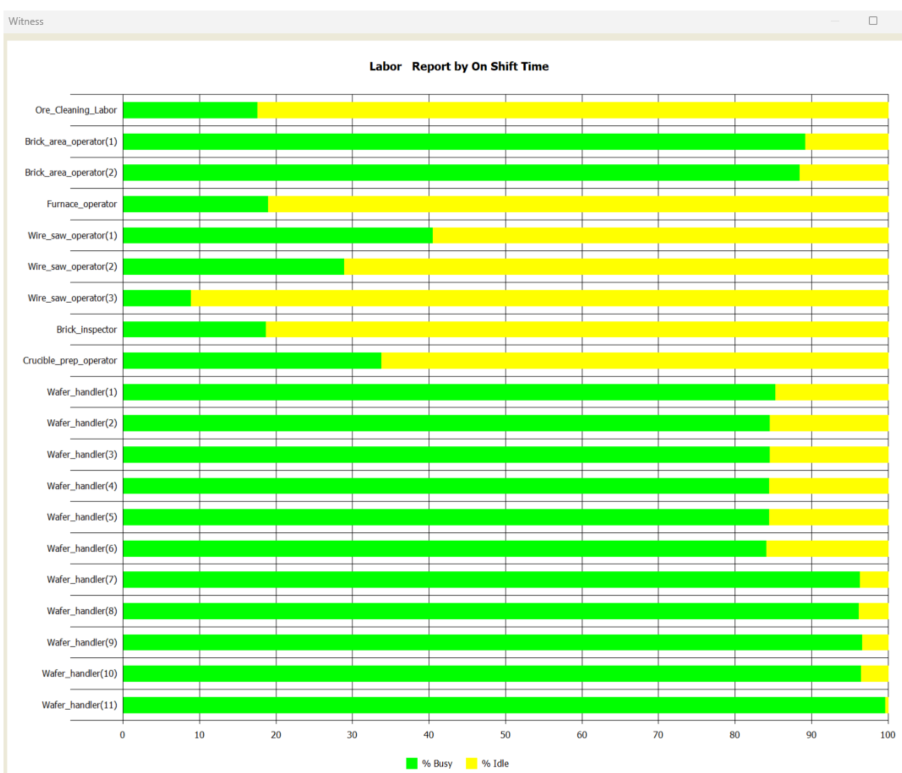

Figure 34 Labor state report for 7th month

8th Month

As seen in the results of the 7th month in Figure 33, most of the machines before the furnace are waiting for labor, adding a second shift can help in this area.

Hence, the following resources are added in the 8th month costing $ 500,000:

1. Crucible prep operator Weekday 2nd Shift – 1
2. Ore cleaner operator Weekday 2nd Shift – 1
3. Furnace operator Weekday 2nd Shift – 1
4. Brick area operator Weekday 2nd Shift – 1
5. Furnace operator Weekday 3rd Shift – 1

As seen in Figure 35, the number of wafer stacks produced has increased to 66,316 and is 126.8% of the monthly production target. The cost per wafer is now $ 0.88 per unit. It can be seen in Figure 36 that the furnace and the crucible fill are not waiting for operator as much as it used to as seen in Figure 33.

Cumulative savings of $50,000 remain for this month.

Statistics Report Report by On Shift Time

Part Machine Buffer Labor Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	141660	0.000	0.000	138960.000	0.000	2700.000	2739.955	9748.251	6.000
Crucible_400Kg	114	0.000	0.000	112.000	0.000	2.000	2.166	9575.409	6.000
Crucible_680Kg	242	0.000	0.000	240.000	0.000	2.000	2.402	5002.782	6.000
By_product	55832	55680.000	0.000	0.000	0.000	152.000	170.311	1537.414	6.000
Grade_A	127905	0.000	0.000	127200.000	0.000	705.000	900.197	3547.158	6.000
Dry_ore	141600	0.000	0.000	138720.000	0.000	2880.000	2812.513	10010.641	6.000
Grade_B	150864	0.000	0.000	149280.000	0.000	1584.000	961.140	3210.935	6.000
Baked_680Kg_Crucible	245	0.000	0.000	240.000	0.000	5.000	3.006	6184.271	6.000
Baked_400Kg_Crucible	113	0.000	0.000	111.000	0.000	2.000	2.368	10561.770	6.000
Filled_680Kg_Crucible	244	0.000	0.000	239.000	0.000	5.000	6.024	12443.034	6.000
Filled_400Kg_Crucible	116	0.000	0.000	112.000	0.000	4.000	3.241	14081.494	6.000
Purified_Ingot	239	0.000	0.000	239.000	0.000	0.000	0.163	344.421	6.000
Brick	16346	0.000	0.000	15687.000	0.000	659.000	445.794	13745.261	6.000
Production_Ingot	112	0.000	0.000	112.000	0.000	0.000	0.580	2611.187	6.000
Block_mount	3497	0.000	0.000	3497.000	0.000	0.000	1.307	188.403	6.000
Chunks	325517	0.000	0.000	324773.000	0.000	744.000	183.575	284.230	6.000
Block_set	897	0.000	14.000	874.000	0.000	9.000	7.749	4354.036	3.653
Stacked_Wafer_box	66316	66316.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	7319717	0.000	683905.000	6631600.000	0.000	4212.000	3266.372	224.906	2.822

Figure 35 Part statistics for 8th month

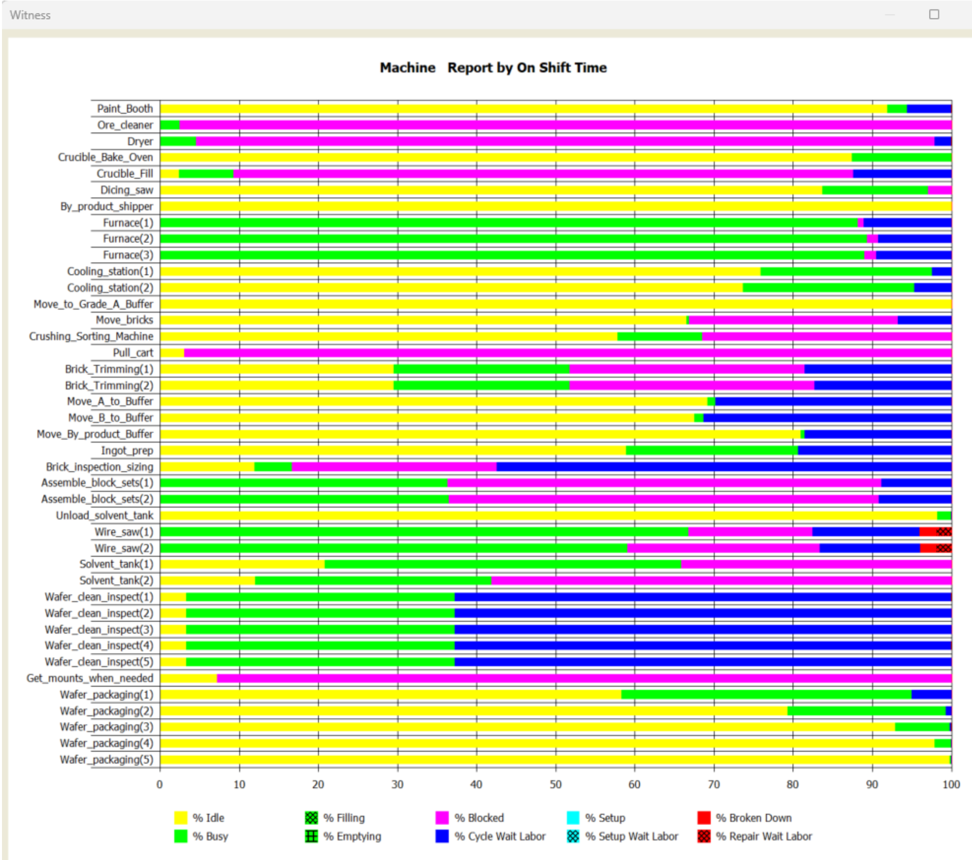

Figure 36 Machine state report for 8th month

Figure 37 Labor state report for 8th month

9th Month

As seen in the results of the 8th month in Figure 36, most of the machines before the furnace are still waiting for labor, adding a weekend shift can help in this area.

Hence, the following resources are added in the 9th month costing $ 500,000:

1. Wafer handler Weekend 1st Shift – 1
2. Furnace operator Weekend 1st Shift – 1
3. Crucible prep operator Weekend 1st Shift – 1
4. Ore cleaner operator Weekend 1st Shift – 1
5. Brick inspector Weekday 2nd Shift – 1

As seen in Figure 38, the number of wafer stacks produced has increased to 70,546 and is 134.89% of the monthly production target. The cost per wafer is now $ 0.89 per unit. It can be seen in Figure 39 that the furnace and the crucible fill machines are not waiting for operator as much as they used to as seen in Figure 36.

Cumulative savings of $50,000 remain for this month.

Statistics Report Report by On Shift Time

Part Machine Buffer Labor Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	151020	0.000	0.000	148320.000	0.000	2700.000	2741.036	9147.677	6.000
Crucible_400Kg	122	0.000	0.000	120.000	0.000	2.000	2.176	8991.230	6.000
Crucible_680Kg	262	0.000	0.000	260.000	0.000	2.000	2.389	4594.946	6.000
By_product	61015	60960.000	0.000	0.000	0.000	55.000	137.275	1133.925	6.000
Grade_A	140115	0.000	0.000	139200.000	0.000	915.000	893.917	3215.461	6.000
Dry_ore	151440	0.000	0.000	148320.000	0.000	3120.000	2861.049	9521.715	6.000
Grade_B	164030	0.000	0.000	163680.000	0.000	350.000	1007.519	3095.713	6.000
Baked_680Kg_Crucible	263	0.000	0.000	260.000	0.000	3.000	3.195	6122.162	6.000
Baked_400Kg_Crucible	124	0.000	0.000	122.000	0.000	2.000	2.339	9507.189	6.000
Filled_680Kg_Crucible	266	0.000	0.000	261.000	0.000	5.000	6.084	11528.449	6.000
Filled_400Kg_Crucible	125	0.000	0.000	121.000	0.000	4.000	3.267	13172.502	6.000
Purified_Ingot	262	0.000	0.000	262.000	0.000	0.000	0.139	268.012	6.000
Brick	17354	0.000	0.000	16658.000	0.000	696.000	653.388	18975.874	6.000
Production_Ingot	121	0.000	0.000	118.000	0.000	3.000	1.694	7055.648	6.000
Block_mount	3720	0.000	0.000	3720.000	0.000	0.000	1.271	172.184	6.000
Chunks	356320	0.000	0.000	356320.000	0.000	0.000	52.321	74.005	6.000
Block_set	954	0.000	15.000	930.000	0.000	9.000	7.672	4052.875	3.650
Stacked_Wafer_box	70546	70546.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	7786456	0.000	727649.000	7054600.000	0.000	4207.000	3235.430	209.422	2.822

Figure 38 Part statistics report for 9th month

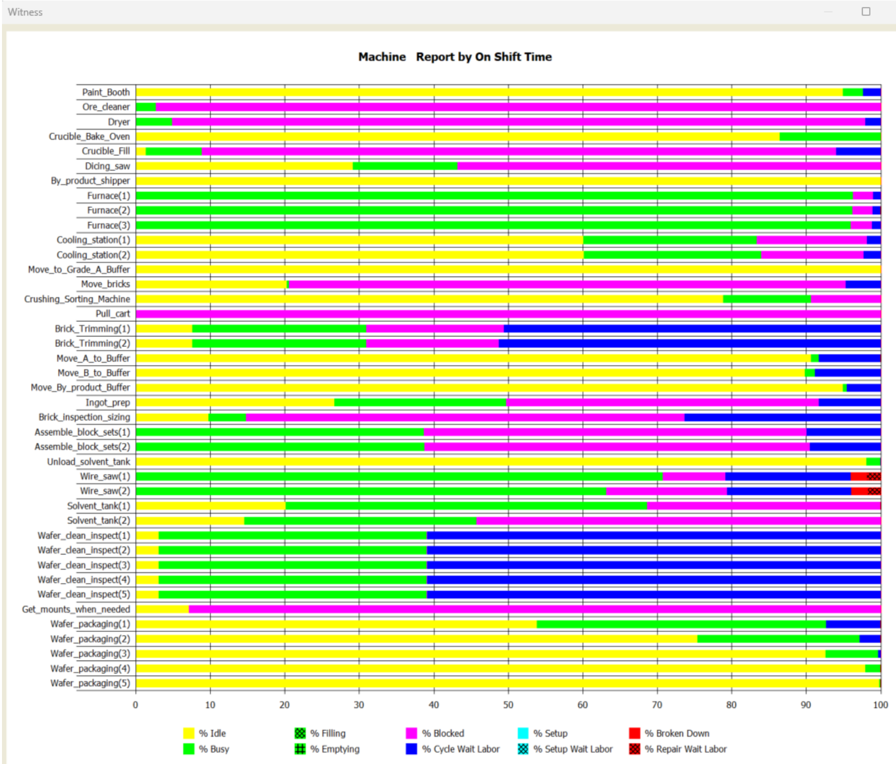

Figure 39 Machine state report for 9th month

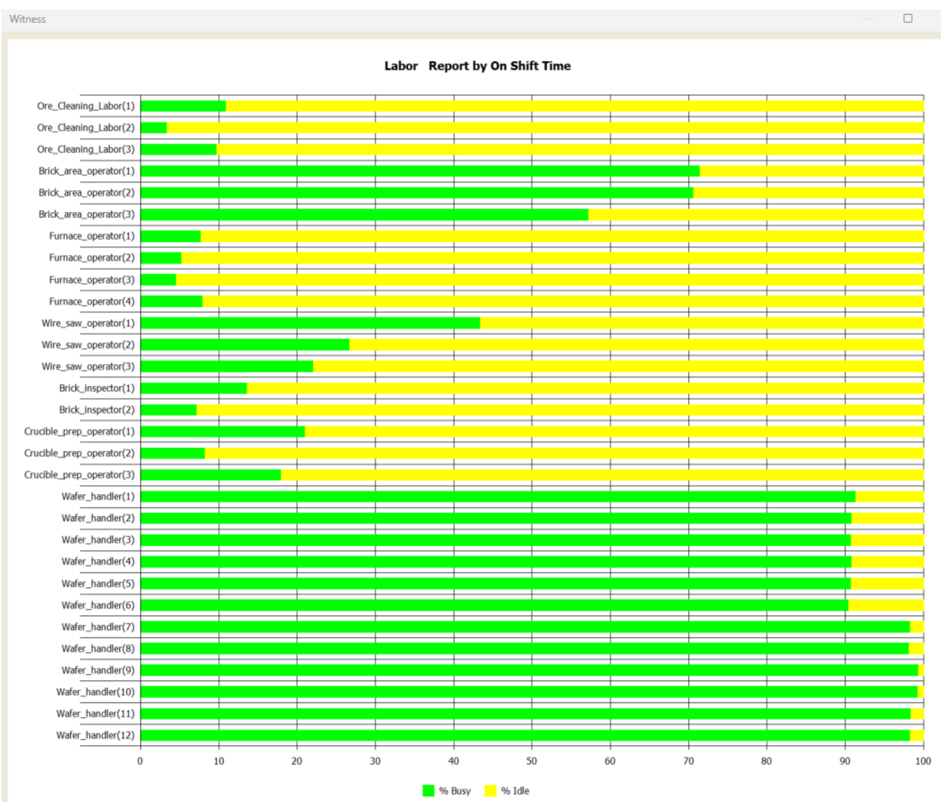

Figure 40 Labor state report for 9th month

10th Month

As seen in the results of the 9th month in Figure 39, most of the machines in the brick production and wire saw area are still waiting for labor, adding a weekday 3rd shift can help in this area.

Hence, the following resources are added in the 10th month costing \$ 300,000:

1. Brick area operator Weekday 3rd Shift – 1
2. Brick inspector Weekday 3rd Shift – 1
3. Wire saw operator Weekday 3rd Shift – 1

As seen in Figure 41, the number of wafer stacks produced has increased to 74,245 and is 141.96% of the monthly production target. The cost per wafer is now \$ 0.89 per unit. It can be seen in Figure 42 that the brick production and wire saw machines are not waiting for operator as much as they used to in Figure 39.

Cumulative savings of \$ 250,000 remain for this month.

Statistics Report Report by On Shift Time

Part Machine Buffer Labor Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	156060	0.000	0.000	153360.000	0.000	2700.000	2748.086	8875.018	6.000
Crucible_400Kg	126	0.000	0.000	124.000	0.000	2.000	2.184	8737.063	6.000
Crucible_680Kg	270	0.000	0.000	268.000	0.000	2.000	2.397	4474.160	6.000
By_product	62388	62160.000	0.000	0.000	0.000	228.000	133.553	1078.905	6.000
Grade_A	143409	0.000	0.000	142720.000	0.000	689.000	821.269	2886.289	6.000
Dry_ore	156000	0.000	0.000	153360.000	0.000	2640.000	2806.372	9066.741	6.000
Grade_B	167783	0.000	0.000	167040.000	0.000	743.000	1010.978	3036.856	6.000
Baked_680Kg_Crucible	270	0.000	0.000	267.000	0.000	3.000	3.236	6039.803	6.000
Baked_400Kg_Crucible	128	0.000	0.000	125.000	0.000	3.000	2.307	9084.102	6.000
Filled_680Kg_Crucible	275	0.000	0.000	269.000	0.000	6.000	6.048	11084.012	6.000
Filled_400Kg_Crucible	127	0.000	0.000	124.000	0.000	3.000	3.289	13053.110	6.000
Purified_Ingot	269	0.000	0.000	268.000	0.000	1.000	0.152	284.349	6.000
Brick	18059	0.000	0.000	17511.000	0.000	548.000	365.709	10206.403	6.000
Production_Ingot	125	0.000	0.000	124.000	0.000	1.000	0.481	1938.702	6.000
Block_mount	3915	0.000	0.000	3915.000	0.000	0.000	1.415	182.174	6.000
Chunks	364480	0.000	0.000	364480.000	0.000	0.000	53.786	74.375	6.000
Block_set	1002	0.000	15.000	978.000	0.000	9.000	7.871	3958.957	3.671
Stacked_Wafer_box	74245	74245.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	8194157	0.000	765698.000	7424500.000	0.000	3959.000	3358.707	206.585	2.822

Figure 41 Part statistics for 10th month

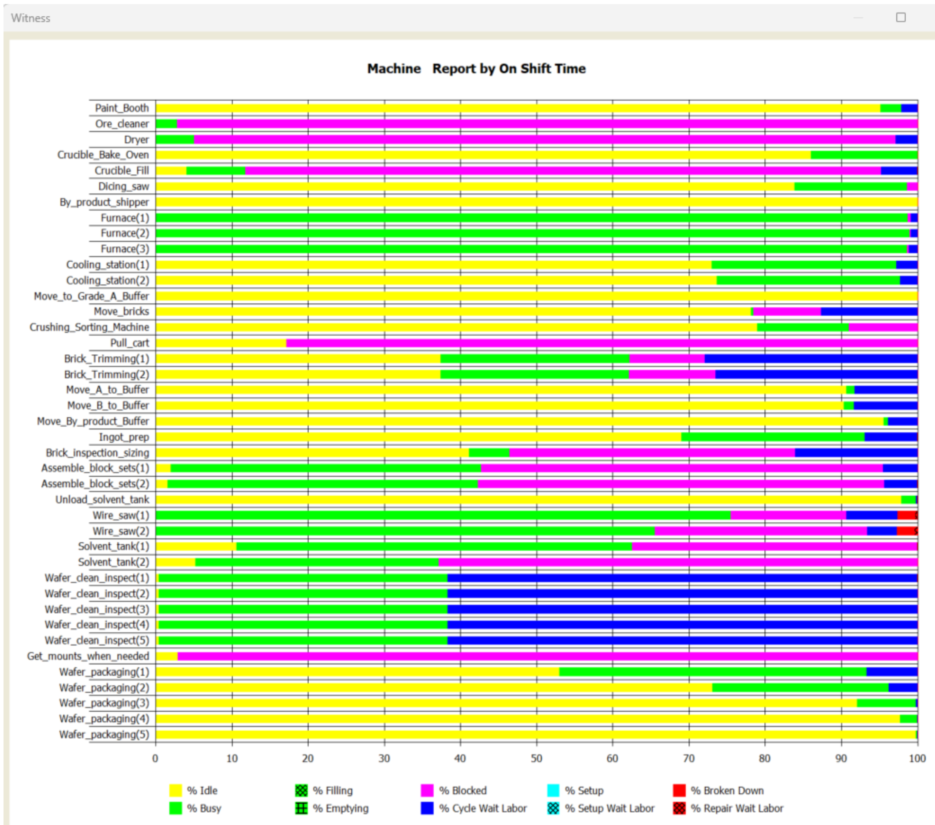

Figure 42 Machine state report for 10th month

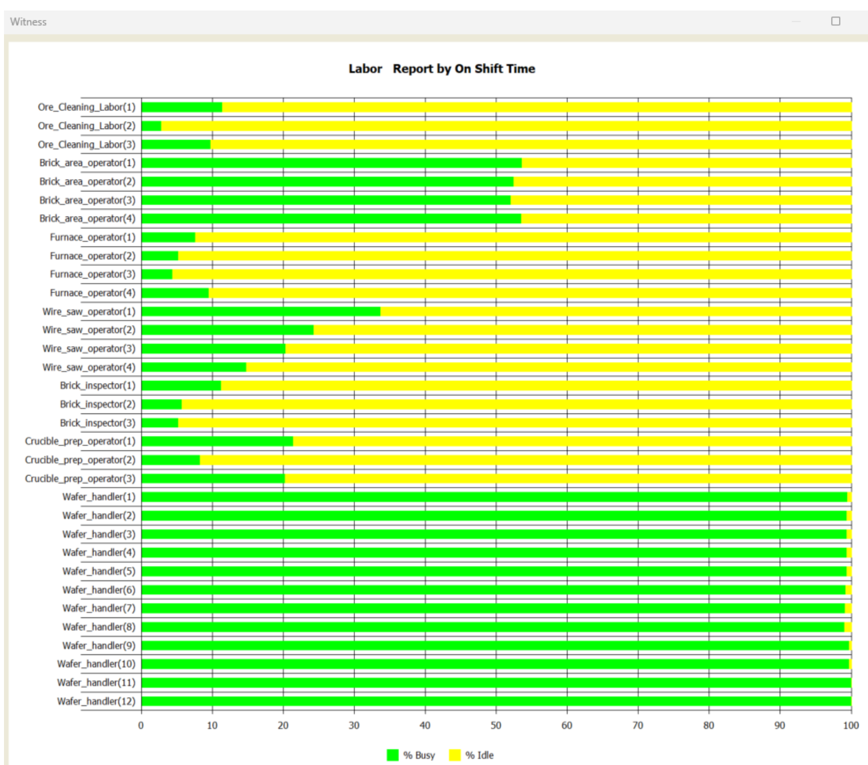

Figure 43 Labor state report 10th month

11th Month

As seen in the results of the 10th month in Figure 43, most of the labor in the wafer cleaning, inspection and packaging area are completely busy. Furthermore, the machines themselves are not idle anymore as seen in Figure 42 indicating that the bottleneck is in this area and the furnaces are moving towards full capacity.

Hence, the following resources are added in the 11th month costing $ 300,000:

1. Wafer handler Weekday 1st Shift – 1
2. Wafer handler Weekday 2nd Shift – 1
3. Wafer handler Weekday 3rd Shift – 1

As seen in Figure 44, the number of wafer stacks produced has increased to 75,893 and is 145.11% of the monthly production target. The cost per wafer is now $ 0.91 per unit. It can be seen in Figure 45 that the wafer cleaning, inspection, and packaging machines are not busy anymore.

Cumulative savings of $ 450,000 remain for this month.

Statistics Report Report by On Shift Time

Part Machine Buffer Labor Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	155340	0.000	0.000	151920.000	0.000	3420.000	2749.177	8919.693	6.000
Crucible_400Kg	126	0.000	0.000	124.000	0.000	2.000	2.184	8735.754	6.000
Crucible_680Kg	270	0.000	0.000	268.000	0.000	2.000	2.393	4467.290	6.000
By_product	62174	62160.000	0.000	0.000	0.000	14.000	133.066	1078.668	6.000
Grade_A	142995	0.000	0.000	142560.000	0.000	435.000	810.219	2855.697	6.000
Dry_ore	154560	0.000	0.000	151680.000	0.000	2880.000	2817.265	9186.735	6.000
Grade_B	167146	0.000	0.000	166320.000	0.000	826.000	1018.659	3071.590	6.000
Baked_680Kg_Crucible	270	0.000	0.000	265.000	0.000	5.000	3.225	6019.524	6.000
Baked_400Kg_Crucible	128	0.000	0.000	125.000	0.000	3.000	2.250	8859.492	6.000
Filled_680Kg_Crucible	273	0.000	0.000	267.000	0.000	6.000	5.992	11061.301	6.000
Filled_400Kg_Crucible	127	0.000	0.000	124.000	0.000	3.000	3.302	13103.268	6.000
Purified_Ingot	267	0.000	0.000	267.000	0.000	0.000	0.151	284.519	6.000
Brick	18010	0.000	0.000	17944.000	0.000	66.000	102.612	2871.537	6.000
Production_Ingot	125	0.000	0.000	124.000	0.000	1.000	0.524	2112.496	6.000
Block_mount	4005	0.000	0.000	4002.000	0.000	3.000	1.110	139.651	6.000
Chunks	363120	0.000	0.000	363120.000	0.000	0.000	58.784	81.591	6.000
Block_set	1025	0.000	16.000	1001.000	0.000	8.000	5.600	2753.605	3.654
Stacked_Wafer_box	75893	75893.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	8374788	0.000	782841.000	7589300.000	0.000	2647.000	2791.707	168.007	2.822

Figure 44 Part statistics report for 11th month

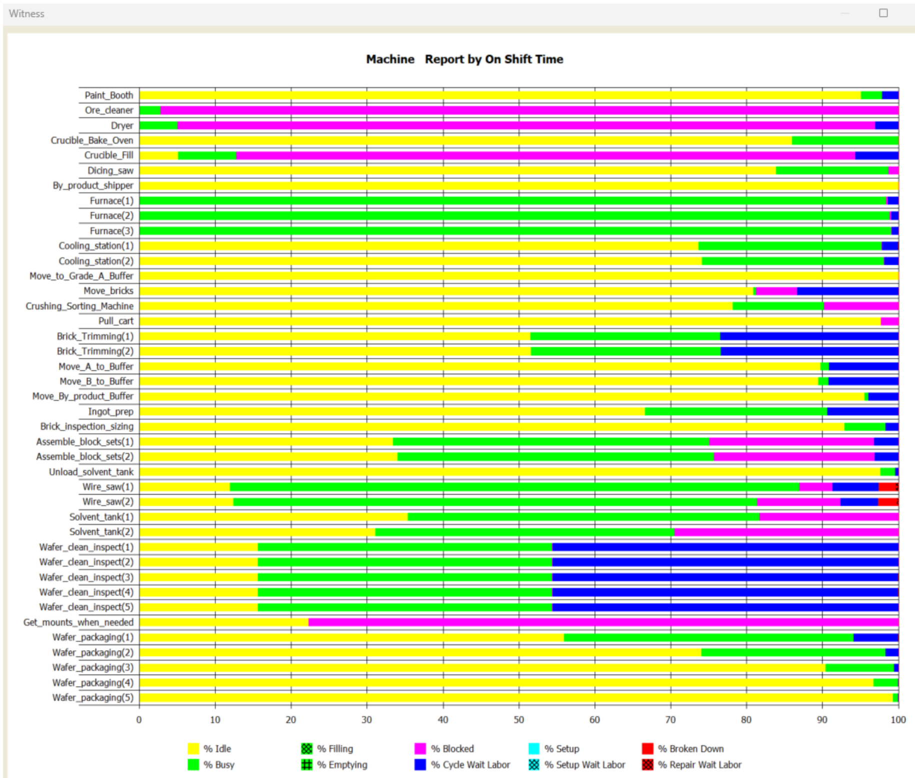

Figure 45 Machine state for 11th month

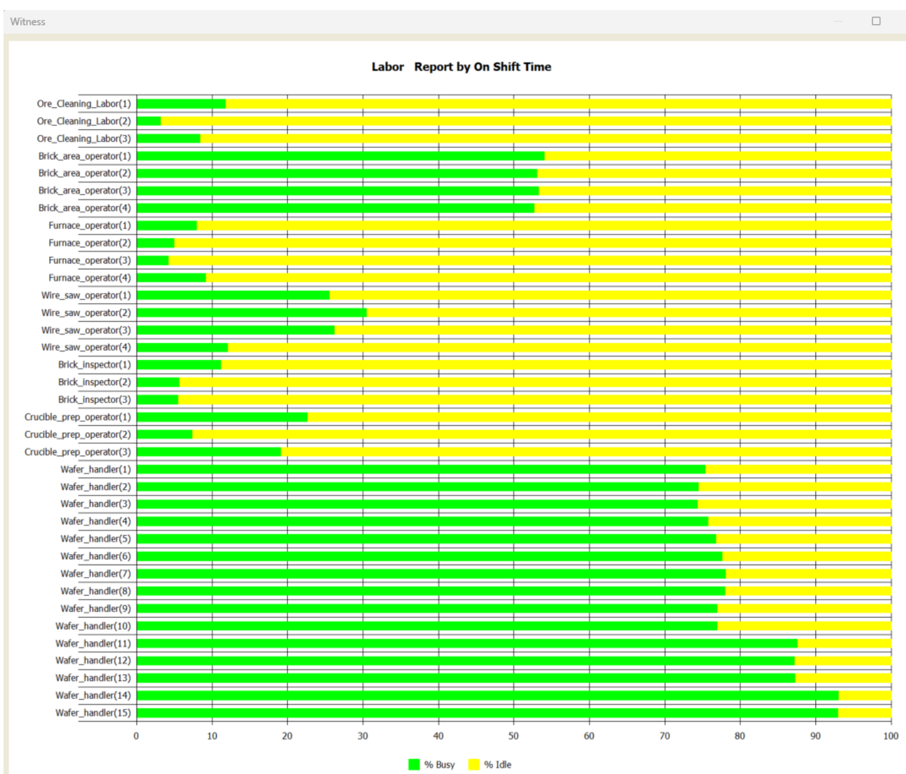

Figure 46 Labor state report 11th month

12th Month

As seen in the results of the 11th month in Figure 45, furnaces are completely busy. Furthermore, if furnaces are added, there would be extra workload on operators downstream in the wafer cleaning, inspection, and packaging area. The cooling stand is also being underutilized consistently and might not be adding any value.

Hence, the following resources are added in the 12th month costing $ 950,000:

1. Furnace – 1
2. Wafer handler Weekend 2nd Shift – 3
3. Wafer handler Weekend 1st Shift – 1
4. Cooling stand – 1 (**sold**)

As seen in Figure 47, the number of wafer stacks produced has increased to 89,562 and is 171.25% of the monthly production target. The cost per wafer is now $ 0.84 per unit. As seen in Figure 48, the bottleneck is now at the wire saw and adding a wire saw machine could help in the future if further increase in production is desired.

All the $6,000,000 has been spent and this is the final configuration of the plant.

Statistics Report   Report by On Shift Time

Part   Machine   Buffer   Labor   Shift

Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
Ore_halfkg	187740	0.000	0.000	185040.000	0.000	2700.000	2774.417	7448.098	6.000
Crucible_400Kg	154	0.000	0.000	152.000	0.000	2.000	2.225	7281.007	6.000
Crucible_680Kg	322	0.000	0.000	320.000	0.000	2.000	2.471	3867.588	6.000
By_product	75029	74880.000	0.000	0.000	0.000	149.000	132.425	889.555	6.000
Grade_A	172045	0.000	0.000	171520.000	0.000	525.000	823.616	2412.756	6.000
Dry_ore	187680	0.000	0.000	185040.000	0.000	2640.000	2828.968	7596.972	6.000
Grade_B	202076	0.000	0.000	201360.000	0.000	716.000	896.481	2235.923	6.000
Baked_680Kg_Crucible	324	0.000	0.000	322.000	0.000	2.000	3.141	4885.397	6.000
Baked_400Kg_Crucible	153	0.000	0.000	150.000	0.000	3.000	2.200	7247.730	6.000
Filled_680Kg_Crucible	329	0.000	0.000	322.000	0.000	7.000	6.645	10179.081	6.000
Filled_400Kg_Crucible	154	0.000	0.000	150.000	0.000	4.000	3.765	12322.769	6.000
Purified_Ingot	322	0.000	0.000	322.000	0.000	0.000	0.147	230.748	6.000
Brick	21739	0.000	0.000	21057.000	0.000	682.000	698.734	16199.537	6.000
Production_Ingot	150	0.000	0.000	148.000	0.000	2.000	1.516	5094.932	6.000
Block_mount	4725	0.000	0.000	4723.000	0.000	2.000	1.112	118.666	6.000
Chunks	437920	0.000	0.000	437920.000	0.000	0.000	64.452	74.177	6.000
Block_set	1206	0.000	17.000	1181.000	0.000	8.000	7.227	3020.305	3.696
Stacked_Wafer_box	89562	89562.000	0.000	0.000	0.000	0.000	0.000	0.000	6.000
Wafer	9883467	0.000	924309.000	8956200.000	0.000	2958.000	2883.242	147.029	2.822

Figure 47 Part statistics report for 12th month

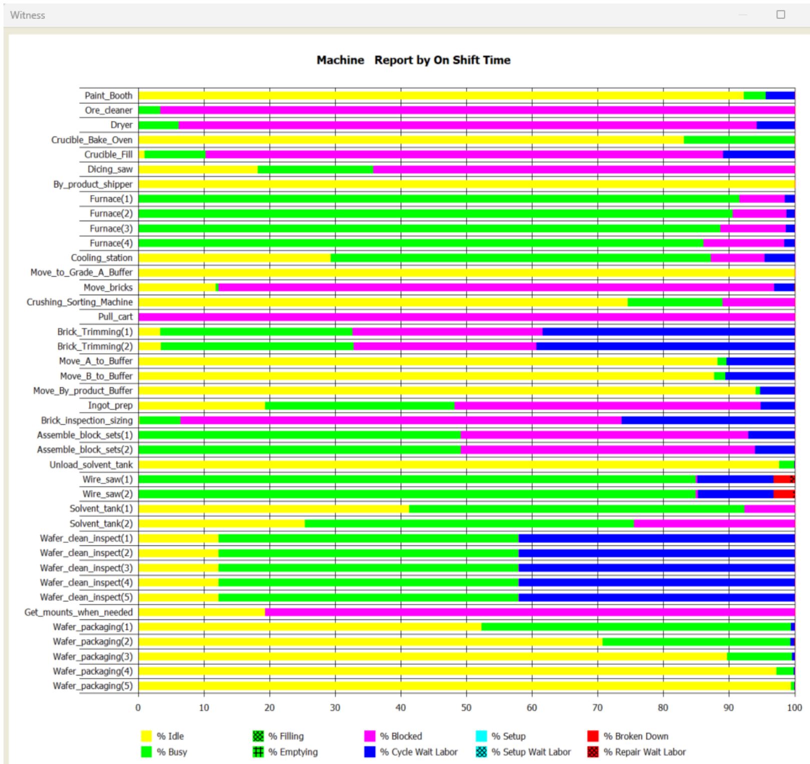

Figure 48 Machine state report for 12th month

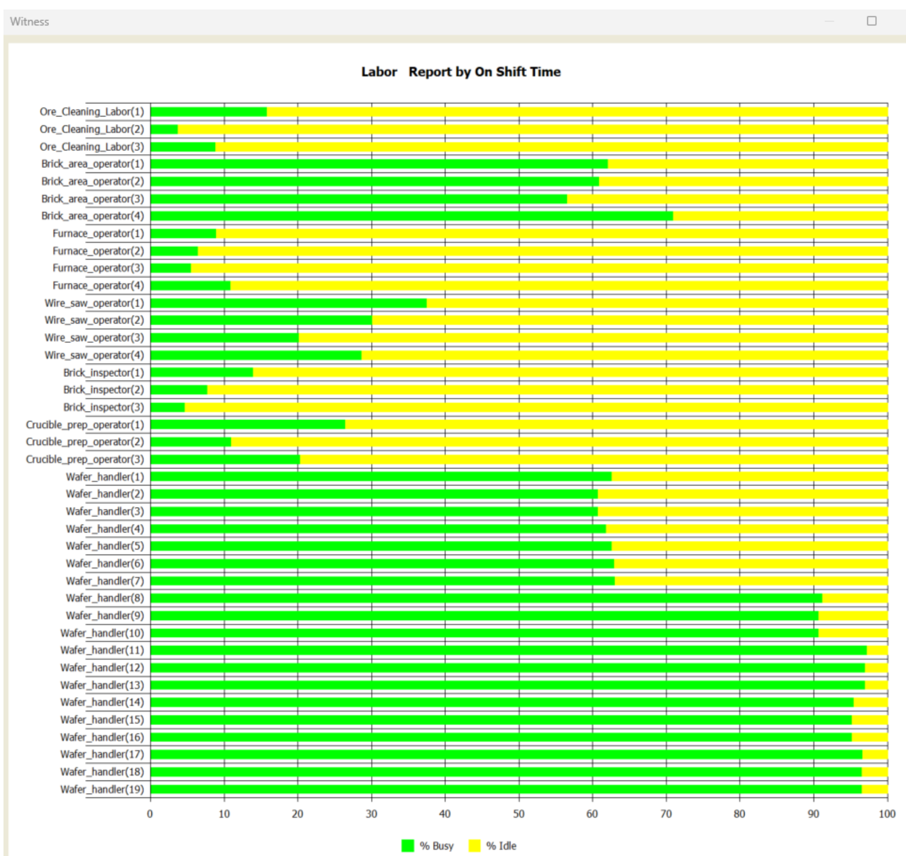

Figure 49 Labor state report for 12th month

An attempt was made to sell (one at a time) the remaining assets that were purchased during the 12 months. However, it leads to loss of production. As seen in Figure 49, all employees other than wafer handlers are not being utilized much. Therefore, costs can be reduced by cross training the following employees and letting go of extra operators:

- Ore cleaning operator
- Crucible prep operator
- Furnace operator
- Brick area operator
- Brick inspector
- Wire saw operator

Below are the tables that show the summary of the resources added in the experiments discussed above where month zero corresponds to the base model:

Table 8 Machines in the facility in each month

Machine	Month / Experiment Number												
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Raw Silicon Cleaning System	1	1	1	1	1	1	1	1	1	1	1	1	1
Raw Silicon Dryer	1	1	1	1	1	1	1	1	1	1	1	1	1
Crucible Spray Booth	1	1	1	1	1	1	1	1	1	1	1	1	1
Crucible Bake Oven	1	1	1	1	1	1	1	1	1	1	1	1	1
Crucible Pack Station	1	1	1	1	1	1	1	1	1	1	1	1	1
Crucible Furnace	1	1	1	2	2	2	2	3	3	3	3	3	4
Cooling Stand	1	1	1	2	2	2	2	2	2	2	2	2	1
Ingot Crusher & Sorting	1	1	1	1	1	1	1	1	1	1	1	1	1
Ingot Prep - Glue Application	1	1	1	1	1	1	1	1	1	1	1	1	1
Ingot Dicing Saw	1	1	1	1	1	1	1	1	1	1	1	1	1
Brick Trim Station	1	1	1	1	1	2	2	2	2	2	2	2	2
Brick Inspection	1	1	1	1	1	1	1	1	1	1	1	1	1
Assemble Block Set	1	1	1	1	1	1	2	2	2	2	2	2	2
Wire Saw	1	1	1	1	2	2	2	2	2	2	2	2	2
Soak Tank	1	2	2	2	2	2	2	2	2	2	2	2	2
Wafer Cleaning, Inspection & Packaging	1	3	3	4	4	5	5	5	5	5	5	5	5

Table 9 Ore cleaning operators needed in each month

Ore Cleaning Operator	**Month / Experiment Number**												
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Weekday 1st Shift	1	1	1	1	1	1	1	1	1	1	1	1	1
Weekday 2nd Shift	0	0	0	0	0	0	0	0	1	1	1	1	1
Weekday 3rd Shift	0	0	0	0	0	0	0	0	0	0	0	0	0
Weekend 1st Shift	0	0	0	0	0	0	0	0	0	1	1	1	1
Weekend 2nd Shift	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 10 Crucible Prep operators needed in each month

Crucible Prep. Operator	**Month / Experiment Number**												
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Weekday 1st Shift	1	1	1	1	1	1	1	1	1	1	1	1	1
Weekday 2nd Shift	0	0	0	0	0	0	0	0	1	1	1	1	1
Weekday 3rd Shift	0	0	0	0	0	0	0	0	0	0	0	0	0
Weekend 1st Shift	0	0	0	0	0	0	0	0	0	1	1	1	1
Weekend 2nd Shift	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 11 Furnace operators needed in each month

Furnace Operator	**Month / Experiment Number**												
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Weekday 1st Shift	1	1	1	1	1	1	1	1	1	1	1	1	1
Weekday 2nd Shift	0	0	0	0	0	0	0	0	1	1	1	1	1
Weekday 3rd Shift	0	0	0	0	0	0	0	0	1	1	1	1	1
Weekend 1st Shift	0	0	0	0	0	0	0	0	0	1	1	1	1
Weekend 2nd Shift	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 12 Brick production operators needed in each month

Brick Production Operator	**Month / Experiment Number**												
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Weekday 1st Shift	1	1	1	1	2	2	2	2	2	2	2	2	2
Weekday 2nd Shift	0	0	0	0	0	0	0	0	1	1	1	1	1
Weekday 3rd Shift	0	0	0	0	0	0	0	0	0	0	1	1	1
Weekend 1st Shift	0	0	0	0	0	0	0	0	0	0	0	0	0
Weekend 2nd Shift	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 13 Brick inspectors needed in each month

Brick Inspector	Month / Experiment Number												
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Weekday 1st Shift	1	1	1	1	1	1	1	1	1	1	1	1	1
Weekday 2nd Shift	0	0	0	0	0	0	0	0	0	1	1	1	1
Weekday 3rd Shift	0	0	0	0	0	0	0	0	0	0	1	1	1
Weekend 1st Shift	0	0	0	0	0	0	0	0	0	0	0	0	0
Weekend 2nd Shift	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 14 Wire saw operators needed in each month

Wire Saw Operator	Month / Experiment Number												
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Weekday 1st Shift	1	1	1	1	1	1	1	1	1	1	1	1	1
Weekday 2nd Shift	0	0	0	0	0	0	0	1	1	1	1	1	1
Weekday 3rd Shift	0	0	0	0	0	0	0	0	0	0	1	1	1
Weekend 1st Shift	0	1	1	1	1	1	1	1	1	1	1	1	1
Weekend 2nd Shift	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 15 Wafer handlers needed in each month

Wafer Handler	Month / Experiment Number												
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Weekday 1st Shift	1	3	4	4	5	5	6	6	6	6	6	7	7
Weekday 2nd Shift	0	0	0	0	0	1	1	2	2	2	2	3	3
Weekday 3rd Shift	0	0	0	0	0	0	0	2	2	2	2	3	3
Weekend 1st Shift	0	0	0	1	1	1	1	1	1	2	2	2	3
Weekend 2nd Shift	0	0	0	0	0	0	0	0	0	0	0	0	3

Figure 50 shows the summary of the experiments where the yearly production and the corresponding cost per wafer is plotted. It also shows the yearly production needed to reach the 1.8 MW per month target set by the company.

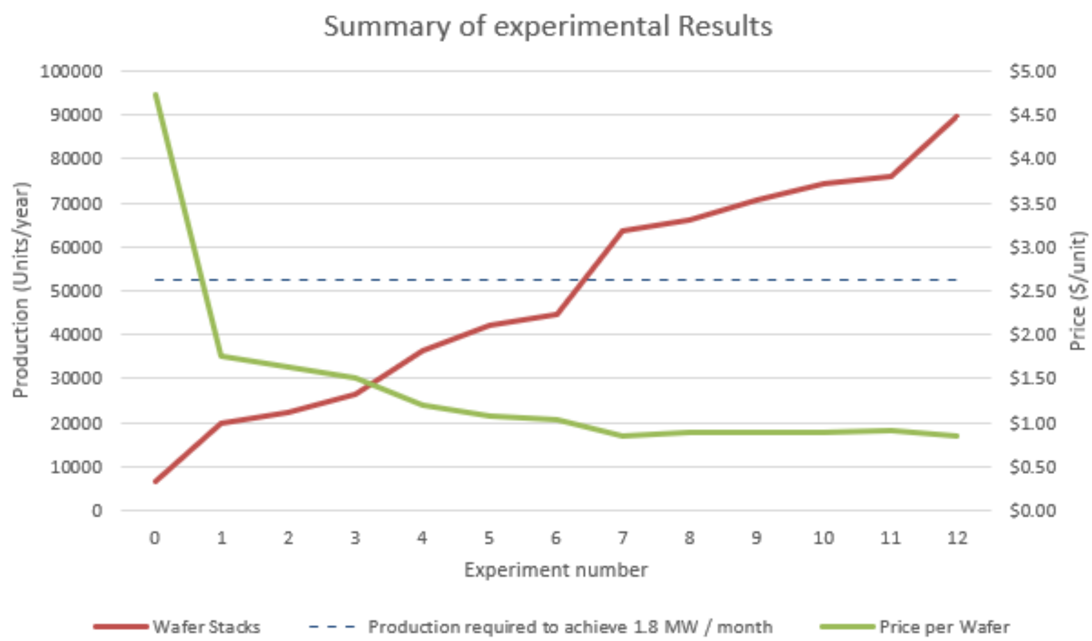

Figure 50 Summary of the experiments

Implementation

This section will discuss the recommendations based on the analysis completed so far and answer specific questions of the NEW's management.

Generate process plan & graphical representation of production process:
A process plan with graphical representation of the production process has been developed as shown in the "System definition" section of this report.

Create deterministic excel spreadsheet to show facility layout:
A deterministic excel spreadsheet showing the cost estimation and the machines and labor requirements for each of the 12 months is attached with this submission for review.

Capital needed for pilot facility:
For the base model (Pilot facility), a capital of $ 5.65 million will be needed for owning machines and $ 700,000 towards hiring operators.

Capital needed for facility that can produce 1.8 MW per month:
The facility which can produce the target of 1.8 MW per month will need $ 3.45 million of investment by 7th month. This is a conservative estimate and hence the actual production could be higher.

Will $ 0.5 million every month over 12 months be sufficient to achieve production of 1.8 MW per month?
The funding provided by NEW will be enough to produce wafers that produce 1.8 MW per month. This capacity can be achieved by the 7th month as seen in Figure 50 with a total investment of $ 3.45 million as shown in the excel spreadsheet. This investment will produce 121.47% with the unit price of each wafer being $ 0.84.

Staffing requirements for pilot facility:
For the pilot facility, one operator will be required in each of the following areas -

1. Ore cleaning
2. Crucible prep.
3. Furnace
4. Brick production
5. Brick inspection
6. Wire saw
7. Wafer handling

Staffing requirements and shift patterns in each of the 12 months:
This can be seen in Tables 9-15 of this report.

Graph that shows the minimum sales price of each wafer for 12 months @ min. ROR of 20% on investment:
This is shown in Figure 50.