Simulation of the Sasol Nitro Watergel Plant using Rockwell Software’s Arena

by

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Interim Project Report
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Executive Summary
Sasol Nitro Ekandustria manufactures a variety of explosives and related accessories. Among these products are watergel products, which are water based explosives produced as cartridges and shipped once gelled. The product line has experienced a recent increase in demand and as such the company requires a tool that will help with decision making for possible projects that have been recommended and could implement as well as the possible identification of additional projects to expand or to debottleneck the facility to increase productivity. To this end simulation will be performed of the current state of the plant with possible improvements being simulated on this model.

Via the simulation, analyses on the possible increases in productivity will be explored against determination of financial implications. Finally a recommendation will be made from the analyses and the data available.

To simulate the plant the system first needs to be studied, including data on the throughput rates of equipment such as the mixers and packaging machines. Breakdowns and interruptions were determined and a detailed methodology for the data gathering is given.

A Literature study was performed giving a brief overview and history on simulation. It also shows possible forms of practical application as well as the advantages to be gained through simulation.

Three weeks were spent gathering and analysing. The data gathered includes the mix times for each different type of batch, including the separate mixing steps’ times and the speed at which the KP (cartridge packaging machine) produces cartridges from this mix. Additional data gathered includes the breakdown times for each separate machine as well as additional mix times from the mix houses’ log books. The data was analysed and recommended mixing times were given and speeds for cartridges that was not measured was calculated by using the straight line method.

With the data the bottlenecks in the system was determined and once the bottlenecks were determined the material handling speed of the plant was determined. It was found that the bottleneck depends on the mix type and the mixing time associated with this mix type as well as the product size of the product being produced. In general the KP is the bottleneck for all cartridges of 29x200mm and smaller, but depending on mix types all cartridges of 29mm diameter and smaller was found to be close to being the bottlenecks with a calculated time of 3 – 6 min/h idle time on the KP at most. For most cartridge sizes the bottleneck was found to be the mix time and the maximum speed that a plant can produce (for V6 mix) was calculated to be 74 boxes per hour.

The analysis of the breakdowns for December found that the average breakdown time for all the KP’s are 5.22 min/h of the total operating time (less lunch times etc). The breakdown times were analysed and a statistic distribution was estimated using the Arena Input Analyser.

An in depth analysis of the model is given with all the logic explained. The detailed steps for expanding the model is given and explained. Once the model was validated for a moth’s sales the different model setups were run. With the results available they are interpreted and analysed with a conclusion given. The recommendation to analyse the long term cost of replacing the existing KPs
versus the cost of maintaining these KPs is given after simulation proved that mix time is the true bottleneck for most sizes and a faster KP will not improve the plant production rate.

Finally a summary of the project and the value of simulation are given.

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Glossary

To avoid any confusion, a list of alphabetically sorted terms, which are present in the proposal, is given below:

- "dd"x"lll"mm (25x270mm): The cartridge size where “dd” (25) refers to the cartridge diameter in mm and “lll” (270) refers to the cartridge length in mm.
- AN Prills: Ammonium nitrate prills (balls) which are fed into the mixer by a conveyor.
- AN Solution: Ammonium nitrate solution.
- B1, B2, B7, and B8: The names of the four pack houses.
- Boxes: Boxes are usually 25kg of product, except for explosmooth products, which is 16kg per box.
- Breakdowns: When a KP stops to fix an error not normal in the process it is referred to as a breakdown.
- Cartridges: Cartridges are round and similar in appearance to “polony” rolls. The mix is pumped into these cartridges.
- Changeover: To manufacture a product that has a different diameter to the previous product manufactured on the same KP the KP needs to be set up for the new diameter.
- Drop / Discharge: When a mix is finished it is discharged (or dropped) into a hopper. The KP pumps the mix from the hopper.
- Explopacks: Product which also contains of watergel mix types but it is packaged into “zip lock” bags by hand.
- KP machine: Short for “Kartridge Pack”. It is the machine that is used to fill cartridges with the explosive product.
- KP operator: The person that operates the KP. These operations include all start-ups and stopping the machine, roll changing or breakdowns repairs.
- Mix / batch: Refers to either a mix type or a single batch of a mix. Mixes are produced in batches.
- Mix house: Refers to the part of the pack house which is used to mix a batch.
- Mixer: The person that mixes the batch or the machine that mixes.
- Pack house: The plant consists of 4 pack houses where the mix is produced and packaged into cartridges. Three of the four pack houses consist of a mix house and a packaging floor, which includes 2 KP’s.
- pH: The mix has to be within a certain pH range to prevent chemical reactions occurring once it has been manufactured.
- PQ: Product used in the mix for all mix types. It is small micro balloons made from plastic and comes in 6 kg bags. The product is very light and very difficult to add to the mix.
- Preparation time: The time during which the pack house is prepared for the shifts production. This preparation includes the positioning of all the relevant packaging/boxing equipment as well as changeovers on the KP’s.
- Roll change: The process to add a new cartridge film to the KP. The KP needs to be stopped for this process.
- Tube film/cartridge film: The film that is used to form the cartridge tube into which the mix is pumped and clipped on the ends by the KP.
• Wire change: The process to change the wire that feeds into the KP. The wire is used to clip the ends of the cartridges. The KP needs to be stopped for this process.
1. Introduction

Sasol Nitro is situated outside Bronkhorstspuit in Ekandustria. The company manufactures a variety of explosives and related accessories. Among their products are their watergel products marketed under the V-“series” of explosives. Recently these explosives experienced a surge in demand and subsequently the plant needs to produce around the clock to meet this demand. A further growth in the demand for the watergel products are expected, with the closing of a related explosives plant in the Sasol group.

Watergel products are available in the V-“series”, consisting of the V4, V6, V8, V10, V12, V-coal and also Explosmooth. Each product’s chemical makeup differs slightly and therefore they need to be mixed in separate batches. The mixing time for each batch differ according to product type and once the batch is mixed it is dropped into a hopper which feeds the “Kartridge Pack” machines (KP1 to KP7). These machines have the capability to package the mixes into cartridges which consists of a variety of diameters and lengths. The diameters can range from 25mm to 200mm (though the 125mm and 200mm are packaged by hand in two very different processes) and the lengths can range from 200mm to 700mm (only 29x700mm in 700mm lengths).

Currently four pack houses exist, B1, B2, B7 and B8, with each of these pack houses (excluding B7) consisting of a mixer and a hopper which feeds two KP’s. B7’s mix is supplied from either B1 or B8 and consists of two hoppers and a single KP. Some of the packaging is also done by hand in B7, primarily the explopacks and the 125x550mm explogels.
Figure 3: Pack house vertical layout
2. Problem definition:
Currently the plant strives to produce sufficient products to meet demand, with the plant often running for 24 hours a day. Reliability of the machines is also a growing concern with old machines often running at full capacity and the parts for the machines which are manufactured in-house (to minimise costs) are not always within the required standards. The results are machines which often have breakdowns that can last for as little as 2 minutes to whole shifts at a time. To ease the stress which is placed on the plant due to the high demand on the plant, management is considering an array of choices to implement. Due to the narrow tolerances within the plant, as well as high capital costs involved in some cases (R2 million for a new KP) they would like to ensure that these choices are worth implementing.

2.1. Specification of required output:
For this project a simulation model of the plant is to be modelled using Arena. Once the model for the current state is validated different situations can be modelled including different managing principles and different equipment. With these situations modelled the impact that these different situations will have on the plant will be measured and compared. For the situations that show an increase in productivity the economic impact will be calculated. This economic analysis will include determining whether the situations or different projects are financially viable according to the company’s Hurdle Rate (or minimum attractive rate of return) as well as the weighted average cost of capital (WACC).

2.2. Planning of project:
The project will consist of three parts, namely:
   A) Process flow and Data gathering
   B) System simulation
   C) Analyses and comparisons

2.1.1. Process flow and data gathering:
During the data gathering phase special attention will be paid to determining all bottlenecks. Time studies will be performed to determine the throughput rates of the machines for all the relevant sizes as well as the different mix type times. Some data mining will also be performed to determine the mix times as well as determining a statistical distribution of the breakdown times the system experiences as well as the machines that experiences these breakdowns.

2.1.2. System simulation
The system simulation will comprise the final part of the project. First a simulation for the current plant will be performed and validated. The plant will be modelled according to the system flow and relevant times identified during the data gathering phase of the project. Once the model has been validated the different managerial principles to run the plant can be modelled as well as the alternative of new equipment being purchased.

2.1.3. Analyses and comparisons
The effect that the different choices will have on the system will readily be seen from the simulation. To determine whether these choices are financially viable certain analyses needs to be performed on these choices to determine if the choices’ rates of return will be higher than the company’s accepted hurdle rate and which of the choices will be the best and whether they can be implemented
simultaneously. For the cases where it is possible to implement choices simultaneously additional simulations can be run to determine the total effect of this implementation.

Figure 4: Process Flow for Project
3. Project Deliverables
To successfully complete the project different Arena simulations will be run and analyses on these simulations will be performed. From these analyses the economical impact of the choices in implementations will be performed and recommendations along with the expected impact of these choices will clearly be shown.
4. Literature Review

4.1. Brief Overview
Simulation is a broad term that is used in many fields, industries and applications, Kelton (2007, p.1). Simulation usually refers to the reproduction of a system that accurately resembles the system it mimics in behaviour and is performed to understand or possibly improve the system, Nance & Sargent (2003, p.161). Recently simulations are usually performed on computers, Kelton (2007, p.1), and although this is not exclusively the case, the growth of computer performance and the ease of access to - and use of computers have helped simulation to grow and gain widespread acceptance.

4.2. History
One of the earliest examples of simulation can be found in Georges Louis Leclerc’s manual Monte Carlo simulation to estimate the value of π, Kelton et al (2007, p.8) and Jansson (1966). It was not uncommon to perform simulation by hand, but the simulation is tedious, difficult and even described as “painful” by some, Kelton et al (2007, p.8).

As is often the case for tools used by Operations Researchers Nance & Sargent (2003, p.162) notes that computer simulation was first used during World War II to simulate continuous and Monte Carlo models. The initial use of computer simulation was limited to large corporations, due to the high costs, and performed by highly educated specialist due to the complexity of the available languages and the sensitivity and high costs required to run the computers, Kelton et al (2007, p.12).

Only when computers became significantly cheaper and faster in the 1970’s and early 1980’s did the modern form of computer simulation with the aid of High-Level Simulator’s make an appearance. Although the value of simulation was rapidly being realized by industries the companies using simulation were still quite large and the simulation itself was usually only used to analyse disasters. During the late 1980’s Simulation was beginning to be embraced by mainstream businesses and in the 1990’s simulation and simulation languages as we know it today were established, Kelton et al (2007, p.12).

4.3. Practical application
Software simulations have become widely accepted and are commonly used as an analysis tool by a variety of industries. It has proved to be an effective technique especially in the design and implementation phases of a project. Simulations are especially popular in the manufacturing industry and can be used for analysis of systems easily described by analytical or mathematical models, Angali et al (2002, p.210). Although other forms of analysis exist, simulation is often the method of choice for more complex systems. Probably the greatest reason for simulation’s popularity lies in the ease with which changes can be implemented in a simulation and the rapid output results that is output from such a simulation which allows experimenting with setups which would otherwise be too expensive or difficult to achieve, Kelton et al (2007, pp.3-4).

Through simulation one hopes to gain a clear solution to a problem. This is only possible if the simulation captures the system along with all its associated “messy” elements and relationships, Van Rensburg & Zwemstra (1995, p.467). There are various steps that can be followed to accurately simulate a system. The IDEF (Integration DEFinition) technique has proved to work well in this
regard, Van Rensburg & Zwemstra (1995), and traditionally most text books give the following set of steps to follow, Nance & Sargent (2003. p.162):

- problem formulation,
- system data collection and conceptual model formulation,
- validation of the conceptual model,
- construction of the simulation program,
- execution of the simulation program,
- operational (results) validation,
- experimental design,
- output data analysis and
- documentation.

Simulation has proved to be an invaluable tool that aids in the understanding of a system as well as the improvement thereof. Complex systems, such as the Panama Canal simulation described by Franzese et al (2004), can be accurately simulated and such simulations can be used to gain invaluable information about both the present and the future system behavior.

It is also important to discern between the continuous/discrete elements of the model, as well as the deterministic/stochastic elements.

4.4. Critique on Simulations

Due to the inherent dependence on stochastic processes to accurately simulate a system’s inputs the outputs will become random as well. For this reason simulations cannot be run only once, but rather over a long time frame to average out the results of such a simulation. Such multiple simulation runs require additional computing power and it is difficult to accurately establish the required number of runs required for accurate average results. To reduce this uncertainty the model can be simplified, but this might cause the model to become inaccurate, Kelton et al (2007, pp.6-7).
5. Data gathering:

5.1. Gathering mix times and assumptions made

From an initial observation it was determined that the two most critical steps in the process are the mixing of the watergel mix and the packaging of the mix. There are three separate mix houses in the watergel plant. Each mix house is operated by two mixers (in one case two mixers and a trainee) and it is assumed that all mix operators are all capable to the same extent. It is also assumed that certain tasks can be performed in parallel or the operators can aid each other in the process, e.g. one operator prepares and gathers the raw material while the second operator starts to mix the next batch.

To determine the times required for a single mix the operators are observed and the times for each step are noted. Once enough data for the mix is gathered the machines will be observed. From the point of observation to observe the KP’s it is also easy to determine how long it takes the mix to be completed and dumped into the hopper. These observation times are important, because the operators are no longer influenced by the observations.

To determine a more accurate time for the mixes the average times for the last three months will be taken. For this a daily production report (from the breakdown logs) will be used and along with the logbook in the mix houses a time can be determined for every mix type. Only days where products which cause the mix to be the bottleneck were manufactured will be analyzed to determine the maximum speed the mix houses usually run on these days. On these product types it can be assumed that the mix house did not have to wait for the pack house except perhaps on the first mix of the shift and after lunch. It is also important to verify that the KP’s ran during the most of the day and that no breakdowns that are unusual were experienced.

5.2. Gathering KP speeds and assumptions made

The KP machines are all the same types of machine and it is assumed that one machine can operate in the same fashion and at comparable speeds to the other machines (with the exception to certain larger sizes such as the 90mm which can only be manufactured by KP3 which is situated in B2). The operators are not directly involved in each cartridge that is produced, but rather the speed at which the machine operates and the setup, tube liner replacements and repairs of each machine. One operator is assigned to one machine and therefore it is assumed that certain tasks, such as preparing a machine for a certain diameter tube, can be performed in parallel.

To determine the KP’s maximum possible speed the number of cartridges that are produced per minute are counted and averaged over a certain time period. Observations of the time it takes to change a tube film and the times in between changes are noted. Further breakdowns are also noted.

5.3. Gathering changeover times

Finally the time it takes to do a changeover from one cartridge diameter to another is also noted.

5.4. Data

The data was collected over a period of three weeks from all four pack houses by means of time study. During this time the data collected covers most of the mixes made, as well as cartridge sizes that cover most of the range of diameters, from 25mm to 200mm, and lengths, ranging from 200mm...
to 700mm. During this time it was noted that the speed for the KP machines between B1 and B2 were almost the same, but B8 always tended to be slower.

The step by step mixing times recorded varied greatly. This is most probably due to the influence the time study had on the operators. When studying the operators directly the times were always longer than the times recorded when standing next to the hopper and merely noting the times between discharges from the mixer. This data is slightly less accurate, because it is difficult to determine if the mix was dropped immediately after it was completed or if the mix operator waited for the KP’s.

### 5.5. What’s in a good mix?

The quality of the mix is directly influenced by the operator who mixes the batch. Recently the plant had problems with the quality of the mixes and for this reason the operators seemed to be highly influenced by the time studies. The time for each separate mix also differs but V4 to V12 seemed to have a clear correlation, with the times increasing slightly according to the amount of PQ and AN Prills that are required by each separate batch. The PQ and AN Prills have been found to be biggest influences on the individual mixing times for the different mixes. V-coal and Explosmooth mixes tend to be more difficult to mix due to the higher amount of PQ required and the inclusion of AN solution, which can heat up the mix too much and it tends difficult to add it to the mix due to a faulty release valve.

It was also noted by one of the KP operators while producing 90x550mm cartridges that the machines have more difficulty when the mix hasn’t gelled properly. These problems seems to increase when the cartridge diameters becomes larger. Should a KP need to restart after it has run out of mix additional wastages can be expected.

One of the areas where the operators save time during the mixing process is during the mixing steps where no material is added to the mix. The step’s importance lies in dissolving the materials to correctly form the chemical reactions. These mix times do not immediately influence the density of the mix and because the pH can easily be adjusted there are no real quality measures that prevent this practice from happening. The long term implications are however more serious due to the pH level changing over time. The mixing sheet has a recommended mixing time of 36 minutes and in the opinion of the analyst this is also quite fast and only possible if everything runs smoothly (AN Prills conveyor doesn’t stall or block and the pH is always correct). More accurate times for each mix will be given.

By analyzing the data from the breakdown logs certain days were picked to determine good mixing time standards. The days were decided on by the amount of breakdowns that occurred as well as the size produced during that day. Only sizes of 32x270mm and larger were considered and for each day only mixes were considered where it was clear that no breakdowns occurred during the mixing of the mix.

### 5.6. B7

B7 doesn’t have its own mixer and usually gets its mix from B8 or occasionally B1. This places additional stress on the mixing operators to prematurely discharge a mix. Because B7 only has one KP machine and the products are often made by hand they tend to produce low numbers of products. The time between batches is also greatly influenced by the time it takes to fetch a batch from either B8 or B1. These times also differ depending on how long the tractor driver needs to wait.
for the next mix to drop before they can load. Measuring the plants capability is very difficult because these times differ so greatly.

In the case of B7 the management philosophy will benefit more by not managing the bottlenecks in B7 but rather by minimizing the stress that B7 places on B8 and B1. It is possible to fetch the mix while the rest of B7 continues to produce and this means it is possible to fetch the mix in smaller batches (2 to 3 portable hoppers or wheelbarrows). This will place less stress on B8 or B1 and it will prevent the mix from setting before it is used. A mix can only be fetched immediately after it has been discharged into the hopper.

5.7. Changeovers
To manufacture a product that has a different diameter to the previous product manufactured on the same KP the KP needs to be set up for the new diameter. This is normal during the start of the shift because the previous product diameter usually differs from one shift to another. The times depend on the size of the diameter (to get the film fed correctly through the machine) as well as the jump in size diameter (if one diameter requires the use of copper wire or not). The average time observed was 29 minutes. This time can be eliminated or minimized if the operator does the changeover while waiting for the mix to be finished.

The changeover times are not influenced by the previous products length or the type of mix that was used by that product. At most it will require a cartridge film roll change and pumping the old mix out of the pipes.

5.8. Film changes and various breakdowns
The film is changed every 31 minutes - this number is the average of all the observations made. All rolls are of the same length and thus this time is independent of cartridge size, but directly dependent on machine speed. This dependence is difficult to measure and for this reason the average of the observations is taken and accepted to be accurate enough. To change a roll takes 2.6 minutes (2 minutes 34 seconds) on average. This equates to 5.04 min/h spent to change a roll. With each roll change wastage can be expected when the machine starts up again.

Breakdowns occur on all machines across the board and vary greatly in the time it takes to fix them. Some are small and take less than 2 minutes to fix, while others can take the whole shift to fix. For a complete summary of the breakdown data see the breakdown section. Due to the age of the machines these breakdowns can occur quite frequently. One of the major issues clearly lies in the clipper heads which constantly jam or don’t seal properly. With each breakdown a certain amount of waste can be expected both before the breakdown and when the machine starts up again. The observed breakdowns last about 9.31 minutes of every hour. This time is merely the observed time and not the same as the time noted in the breakdown logs. It is also the average for all the machines observed whereas the breakdown logs are machine specific.

When the mix is the system’s bottleneck these breakdowns and roll changes don’t have an important effect on the overall production of the plant, but when the KP is the bottleneck the time lost cuts directly into the production that the plant can deliver. When doing the system analysis it is assumed that both the machines will run, unless only one machine can produce (as in the case for any 90mm product). This assumption has a significant influence on the overall capability study and
will also bring to light important management principles and decisions that will be required when managing the plants.

For the analysis the breakdowns times for KP1 and KP2 of B1 are used, unless it is only sizes that KP3 can produce, in which case the breakdown times for KP3 will be used.

5.9. **Jumbo Mumbo (200x550mm cartridges)**
The determination for the speed to produce a jumbo proved to be somewhat difficult, but it was found that a single mix can be boxed within 25 minutes, which is much less time than should be possible to mix a batch. When analysis was done multiple boxes were prepared before the packaging began and while this would be a good standard operating procedure the number of boxes were equal to the whole day’s production, which is too much. It would be recommended that they wait for the mix to be finished then prepare boxes until the batch is dropped, or if the batch drops before they are ready they only need to prepare enough boxes for the batch. Once the batch is ready and they have enough boxes they can start producing.

Generally they should be able to produce enough boxes for a batch in the same time it would take to mix a batch (=45min), as they normally are able to keep up (for normal sizes where the KP’s are used) and the boxes for jumbo’s only take marginally longer. If too many boxes are prepared before they start production they will have too much idle time and subsequently the production will be lower than possible.
6. Data analysis

6.1. Cartridge size analysis

For the purpose of analyzing the data the V6 product line will be analysed, since the mix times are the most accurate for this. The mix type does not influence the machine’s cartridge speed, but due to density differences between the types it does influence the kg/hour speed.

From Table 1: Machine speeds for V6 mix. it can clearly be seen that, for an average mixing time of 48.5 minutes per batch, only the smallest cartridges limit the plant material handling speed. Ignoring the effect of breakdowns and roll changes all products larger than 25mmx270mm the machine can process the mix faster than it can be prepared. However once one considers the effect of the breakdowns and roll changes the machines still cannot process the mix faster than it can be made for 29mmx270mm and smaller. Therefore the mixing time is only seen as the bottleneck for all products larger than 29mmx270mm. The total idle time that the KP’s experience for the remaining 29mm diameter cartridges are 3 to 6 minutes (depending on length) and therefore even though they are not technically bottlenecks, they are still very close to being bottlenecks.

The effect the diameter has on the speed of the machine (kg/minute) can be seen in Figure 5: Diameter vs. Speed for 270mm long cartridges. and Figure 6: Diameter vs. Speed for 550 mm long cartridges. Figure 5: Diameter vs. Speed for 270mm long cartridges. shows the data for cartridges with diameters of 25mm, 29mm, 32mm, 38mm, 45mm and 50 mm and with lengths of 270mm each. Figure 6: Diameter vs. Speed for 550 mm long cartridges. represents the data for cartridges with diameters of 25mm, 29mm, 32mm, 38mm and 90mm each with a length of 550mm. From these figures it is clear that the size of the diameter has a direct effect on the speed of the machine with an increasing diameter directly increasing the speed.

From Figure 5: Diameter vs. Speed for 270mm long cartridges. it is clear that the increase in speed is almost linearly related to the diameter except for the 45x270mm cartridges. Looking at the graph it can clearly be seen that the speed is an anomaly and looking at the actual data confirms this, because the observed cartridge/minute speed is in fact slower than that of the 50x270mm cartridges.
The effect the lengths of the cartridges have on the speed is slightly less clear and can be seen in Figure 7: Length vs. Speed for different cartridge diameters. It appears that the increase in length initially increases the speed, but the increase the length has on the speed eventually evens out. This probably happens when the clipper speed is no longer slower than the speed that the machine can pump the cartridge full or, in other words, the only advantage a longer cartridge has is that the machines don’t need to clip as often. The machine continuously pumps the cartridge full and doesn’t stop while clipping the previous cartridge.
Looking at Figure 8: Speed vs. Diameter for both 270mm and 550mm. where the speed vs. diameter is analyzed for both 270mm and 550mm lengths the higher influence the length has on the material handling speed for larger diameter sized cartridges can more easily be seen. Looking at the 25mm and 29mm diameter cartridges it can be seen that there is very little difference in the relative speed, but for 32mm diameter cartridges a more significant difference in the length can be seen and this is even more likely when comparing the speeds for the 38mm diameter cartridges.
<table>
<thead>
<tr>
<th>DIAMETER</th>
<th>LENGTH</th>
<th>DENSITY</th>
<th>VOL</th>
<th>MASS</th>
<th>CART. COUNT</th>
<th>Speed (Cart/min)</th>
<th>KG/MIN</th>
<th>kg/hour</th>
<th>KP's running</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>270</td>
<td>1.16</td>
<td>132.54</td>
<td>153.74</td>
<td>162.61</td>
<td>99.32</td>
<td>15.27</td>
<td>916.19</td>
<td>2</td>
</tr>
<tr>
<td>25</td>
<td>550</td>
<td>1.16</td>
<td>269.98</td>
<td>313.18</td>
<td>79.83</td>
<td>51.86</td>
<td>16.24</td>
<td>974.43</td>
<td>2</td>
</tr>
<tr>
<td>29</td>
<td>200</td>
<td>1.16</td>
<td>132.10</td>
<td>153.24</td>
<td>163.14</td>
<td>115.00</td>
<td>17.62</td>
<td>1057.40</td>
<td>2</td>
</tr>
<tr>
<td>29</td>
<td>270</td>
<td>1.16</td>
<td>178.34</td>
<td>206.87</td>
<td>120.85</td>
<td>106.46</td>
<td>22.02</td>
<td>1321.37</td>
<td>2</td>
</tr>
<tr>
<td>29</td>
<td>550</td>
<td>1.16</td>
<td>363.29</td>
<td>421.41</td>
<td>59.32</td>
<td>52.89</td>
<td>22.29</td>
<td>1337.38</td>
<td>2</td>
</tr>
<tr>
<td>29</td>
<td>700</td>
<td>1.16</td>
<td>462.36</td>
<td>536.34</td>
<td>46.61</td>
<td>44.46</td>
<td>23.84</td>
<td>1430.69</td>
<td>2</td>
</tr>
<tr>
<td>32</td>
<td>270</td>
<td>1.16</td>
<td>217.15</td>
<td>251.89</td>
<td>99.25</td>
<td>108.80</td>
<td>27.41</td>
<td>1644.33</td>
<td>2</td>
</tr>
<tr>
<td>32</td>
<td>550</td>
<td>1.16</td>
<td>442.34</td>
<td>513.11</td>
<td>48.72</td>
<td>59.40</td>
<td>30.48</td>
<td>1828.72</td>
<td>2</td>
</tr>
<tr>
<td>38</td>
<td>270</td>
<td>1.16</td>
<td>306.21</td>
<td>723.57</td>
<td>34.55</td>
<td>77.90</td>
<td>56.37</td>
<td>3381.94</td>
<td>1</td>
</tr>
<tr>
<td>38</td>
<td>550</td>
<td>1.16</td>
<td>623.76</td>
<td>4058.78</td>
<td>74.28</td>
<td>1.96</td>
<td>4.51</td>
<td>2422.54</td>
<td>2</td>
</tr>
<tr>
<td>45</td>
<td>270</td>
<td>1.16</td>
<td>429.42</td>
<td>530.14</td>
<td>40.65</td>
<td>100.00</td>
<td>61.50</td>
<td>3689.80</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>270</td>
<td>1.16</td>
<td>498.12</td>
<td>614.97</td>
<td>50.19</td>
<td>81.06</td>
<td>40.38</td>
<td>1430.69</td>
<td>2</td>
</tr>
<tr>
<td>90</td>
<td>550</td>
<td>1.16</td>
<td>3498.95</td>
<td>4058.78</td>
<td>74.28</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>125</td>
<td>550</td>
<td>1.16</td>
<td>6749.52</td>
<td>7829.44</td>
<td>74.28</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>200</td>
<td>550</td>
<td>1.16</td>
<td>25000.00</td>
<td>25000.00</td>
<td>74.28</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 1: Machine speeds for V6 mix.
6.2. Analysis of Mixing Times

For the analysis of the mixing times both individual time studies and data mining from the breakdown logs and the mix logbooks was done. The individual time studies showed to be inaccurate to determine the complete mixing time, due to the fact that the presence of the analyst influenced the mixers, but it proved to be necessary to determine the most important differences between the different mixes. In the case of the V series (V4-V12) it was found to be the amount of AN Prills and the amount of PQ to be added to the mix. In the case of V-coal and Explosmooth the large amount of PQ and the AN solution proved to be the most determining factors for the mixing time.

From the data analysis of the production for the month of December a group of dependable mix times were gathered (where the production ran smoothly and the mix time was the bottleneck, i.e. large diameters) and an average time was compiled. These times were then used, along with the knowledge from the time studies to give a recommended time for each mix. These times will be used as the mixing times. With more accurate knowledge or with better processes these times can be adjusted at a later stage.

The measured times (both from time studies and data analysis) as well as the recommended times are listed in the table below.

<table>
<thead>
<tr>
<th></th>
<th>Measured time</th>
<th>Recommended time</th>
</tr>
</thead>
<tbody>
<tr>
<td>E90</td>
<td>55.28</td>
<td>55</td>
</tr>
<tr>
<td>V-coal</td>
<td>48.50</td>
<td>49</td>
</tr>
<tr>
<td>V4</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>V6</td>
<td>48.50</td>
<td>48.5</td>
</tr>
<tr>
<td>V8</td>
<td>50.79</td>
<td>50</td>
</tr>
<tr>
<td>V10</td>
<td>48.53</td>
<td>47</td>
</tr>
<tr>
<td>V12</td>
<td>47.50</td>
<td>45</td>
</tr>
</tbody>
</table>

Table 2: Mix times
7. Breakdown analysis

The breakdown logs for the months December were read into Excel and then analyzed for each pack house and KP. From the data gathered the following tables serve as a summary of the data gathered where all times are in minutes unless otherwise stated:

<table>
<thead>
<tr>
<th>B1</th>
<th>KP1</th>
<th>KP2</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdowns:</td>
<td>All idle time breakdowns</td>
<td>All idle time breakdowns</td>
<td></td>
</tr>
<tr>
<td>Avg down time</td>
<td>41.45</td>
<td>62.16</td>
<td></td>
</tr>
<tr>
<td>Minimum down time</td>
<td>5.00</td>
<td>10.00</td>
<td></td>
</tr>
<tr>
<td>Maximum down time</td>
<td>110.00</td>
<td>310.00</td>
<td></td>
</tr>
<tr>
<td>Number of Breaks</td>
<td>22.00</td>
<td>25.00</td>
<td></td>
</tr>
<tr>
<td>Per shift avg</td>
<td>109.62</td>
<td>28.50</td>
<td>130.51</td>
</tr>
<tr>
<td>Number of shifts</td>
<td>37.00</td>
<td>37.00</td>
<td></td>
</tr>
<tr>
<td>Breakdown min/hour avg</td>
<td>2.53</td>
<td>4.85</td>
<td>3.69</td>
</tr>
<tr>
<td>Min/hour less idle avg</td>
<td>2.87</td>
<td>5.82</td>
<td>4.35</td>
</tr>
<tr>
<td>Idle min/hour avg</td>
<td>12.11</td>
<td>14.60</td>
<td>13.35</td>
</tr>
<tr>
<td>Sample Std Dev</td>
<td>30.5</td>
<td>64.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Breakdown analysis for B1.

The 110 minute breakdown on KP1 was caused by a clipper head problem and the 310 minute breakdown was caused by a mandril problem.

Using the breakdown times for December in the Input analyser supplied with Arena the statistical distributions for KP1 and KP2 are given below.

KP1:

- Distribution: Beta
- Expression: 5 + 105 \* BETA(0.588, 1.11)
- Square Error: 0.008731

KP2:

- Distribution: Weibull
- Expression: 10 + WEIB(48, 0.84)
- Square Error: 0.002935
Table 4: Breakdown analysis for B2.

The 345 minute breakdown on KP3 was caused by a wire problem and the 210 minute breakdown on KP4 was caused by a clipper head problem.

Statistical Distributions for KP3 and KP4

KP3:

- Distribution: Beta
- Expression: 15 + 330 * BETA(0.315, 0.447)
- Square Error: 0.035652

KP4:

- Distribution: Uniform
- Expression: UNIF(15, 210)
- Square Error: 0.014286

Table 5: Breakdowns analysis for B7 (KP5).

The 180min breakdown on KP5 was caused by an extruder problem.
Statistical Distribution for KP5:

- Distribution: Exponential
- Expression: 30 + EXPO(52)
- Square Error: 0.037905

### B8

<table>
<thead>
<tr>
<th>Breakdowns:</th>
<th>KP6</th>
<th>KP7</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>All idle time breakdowns</td>
<td>127.27</td>
<td>88.71</td>
<td></td>
</tr>
<tr>
<td>Minimum down time</td>
<td>12.00</td>
<td>12.00</td>
<td></td>
</tr>
<tr>
<td>Maximum down time</td>
<td>568.00</td>
<td>340.00</td>
<td></td>
</tr>
<tr>
<td>Number of Breaks</td>
<td>15.00</td>
<td>14.00</td>
<td></td>
</tr>
<tr>
<td>Per shift avg:</td>
<td>149.11</td>
<td>55.83</td>
<td>143.06</td>
</tr>
<tr>
<td>Number of shifts</td>
<td>35.00</td>
<td>33.00</td>
<td></td>
</tr>
<tr>
<td>Breakdn min/hour avg:</td>
<td>5.51</td>
<td>4.89</td>
<td>5.20</td>
</tr>
<tr>
<td>min/hour less idle avg:</td>
<td>6.38</td>
<td>5.53</td>
<td>5.95</td>
</tr>
<tr>
<td>idle min/hour avg:</td>
<td>16.46</td>
<td>16.56</td>
<td>16.51</td>
</tr>
<tr>
<td>Sample Std Dev</td>
<td>152</td>
<td>97.9</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Breakdown analysis for B8.

The 568 minute breakdown on KP6 was caused by an electrical problem and the 340 minute breakdown was caused by a jammed up sump.

Statistical distributions for KP6 and KP7

**KP6:**

- Distribution: Weibull
- Expression: 12 + WEIB(86.8, 0.62)
- Square Error: 0.015934

**KP7:**

- Distribution: Weibull
- Expression: 12 + WEIB(56.3, 0.591)
- Square Error: 0.013662

The average breakdown time during a shift is 47 minutes. During the month of December 111 breakdowns were noted, totalling to 9662 minutes and an overall plant average of 284 minutes per shift. The shortest breakdown noted was 5 minutes and the longest 568 minutes. Both KP1 and KP2 showed the highest count of breakdowns, but because they both noted the shortest breakdowns and are both part of B1 it is possible that the operators are more precise about noting the breakdowns and note smaller breakdowns than the other operators. The lowest min/hour breakdown time at 4.35 minutes downtime for every hour of operation for B1 also supports this theory. The highest per shift average for a plant was noted by B2, with KP3 noting the highest average breakdown time in the plant.

By viewing the breakdown time for every hour of operation B1 seems to be the most available plant with KP1 the most available KP, but with KP5 and KP7 both more available than KP2. The least
available plant seems to be B2 with KP2 showing more breakdown time than KP3. This is probably caused by the fact that KP2 is more often in operation than KP3, because KP2 is usually exclusively used for diameters of 50mm and larger. KP6 shows the most breakdown time for December, which is probably due to the one very large breakdown it had.

In terms of the idle min/hour time B7 appears to be the most productive with an 11.17 min/hour idle time noted. B7 is followed by B1, with 13.35 min/hour average, B8, with 16.68 min/hour average and B2 with a 17.77 min/hour average. The min/hour idle time is determined by all the idle time throughout the whole shift time, which would include lunches and preparation times etc.
8. Determining cartridge speeds

Not all the sizes produced in the product line were analysed during the course of the analysis. For these sizes it will be required to determine the speed either through interpolation or other mathematical form of determination.

The maximum speed that a KP can produce at is quoted to be 120 cartridges per minute, with actual measurements at 118 cartridges per minute without failures taken into consideration. The speeds used in the model are the cartridge speeds less the fails that were recorded. The maximum speed recorded was 115 cartridges per minute for 29x200mm and thus we know that this should be the fastest possible speed for any KP. The speed that will be used for all cartridges smaller than 29x200mm is chosen to be 100 cart/min, i.e. 25x200mm and 25x100mm. The reason for this decision is that the only cartridges smaller are all 25mm diameters and the fastest recorded speed for this size is 99 cart/min.

All cartridge speeds for cartridges that are 270mm in length can be determined by assuming that the speeds are determined by the straight line relationship:

\[ \frac{\text{y}}{\text{g1877}} = \frac{\text{\text{\textit{g1865}}}}{\text{\text{g1876}}} + \frac{\text{\text{\textit{g1855}}}}{\text{\text{\textit{g1856}}}} \]

Equation 1: Straight line equation

With \( y \) the speed in kg/min, \( x \) the diameter in mm, \( m \) the straight line angle and \( c \) the constant. Using the two points for the 25mm and 50 mm cartridges it is found that \( m = 1.97 \) and \( c = -37 \). Replacing these values into the straight line equation it becomes:

\[ y = 1.97x - 37 \]

Equation 2: Straight line equation to determine the speed for 270mm cartridges.

Once the speed in kg/min is known the speed in cartridges/minute is determined in equation:

\[
\text{speed (cart/min)} = \frac{\text{speed (kg/min)} \times 1000}{\text{mass (kg/cart)}}
\]

Equation 3: Determining speed in (cart/min)

With these equations the recommended speed for 45x270mm becomes 103.7 cartridges/minute and for 65x270mm cartridges the recommended speed is 87.6 cartridges/minute.

Using the 29mm diameter and 90mm diameter points on the graph 550mm length cartridges the straight line equation becomes:

\[ y = 2.06x - 37.7 \]

Equation 4: Straight line equation to determine the speed for 550mm long cartridges

With equations 4 and 3 the speed can be determined for all cartridges that are 550 mm long and have not been measured. 45x550mm = 54.2 cart/min, 50x550mm = 52.13 cart/min, 65x550mm = 45.44 cart/min and 80x550mm = 39.63 cart/min
Because it was found that the influence that length has on 25mm diameter cartridges is negligible, especially for cartridges longer than 270mm, the speed for 25x600mm cartridges is determined to be 48.94 cart/min (using equation 3 with a speed of 22.5 kg/min).

Figure 9: Diameter vs. Speed for 270mm lengths with estimated speeds

Figure 10: Diameter vs. Speed for 550mm lengths with estimated speeds
9. Arena Model

9.1. Approach
The model is simulated using Rockwell Software’s Arena V11. First the model was built with a bare bone approach with only one mix and one cartridge size. In this case it was simulated with V6 mix, which has the highest accuracy in the measured data, and 29x270mm cartridges, which is the size that’s highest in demand and thus also has the most measured and most accurate data. The model consists of two separate forms of logic which is built independently but functions together.

The mix side is modelled with a mixing tank and a hopper. The mix is again a separate logic with its own station. All the ingredients are added separately and individual delays are allocated to each step according to the time study measurements. The packaging side is modelled with two KP’s each with relevant speeds and downtimes (breakdowns are specific to each KP) according to the time study measurements and calculated estimates (see Sections 6 through 8). Finally the products are boxed before they leave the system.

Once the bare bone model was validated it was further expanded to include all mix types and sizes that are manufactured. The model was run with product specifications, such as mix type and size, according to previous months’ sales. The model was again validated for these specifications and once the model was accurate enough the complete plant was simulated to include pack houses B1, B2 and B8. The model was validated for a final time and once validated different models, each with its own modification, was run.

9.2. Model Details

9.2.1. Mix house model
For each pack house B1, B2 and B8 the mixer and hopper tank is modelled separately from the cartridge packagers and boxers. Though the logic might be separate both parts of the logic access the hopper tank.

The mix type, product size and batch order sizes (in boxes) are assigned to global variables for each pack house. Both the current size/mix type as well as the future size/mix type are assigned to variables and both these sets of variables are used to determine the need for a changeover once the order has been fulfilled. The changeovers are handled by the pack house logic.
The pack house station involves the seizing of mix operators as well as determining if an additional batch of the current mix is required or if the next mix type should be mixed.

Once the mix type has been assigned a mix type it will be transported to a relevant mixing process. This process involves a delay for the specific mix. Once all the mixing steps are completed the mix in the mixing tank will be transferred to the hopper from where the KP’s will pump the mix into the cartridge film to create the final product. The mix will only be transferred to the main tank once it is empty or, in the case where the new mix is the same as the previous mix, once there is enough space for the new mix to be added.

As soon as the mix is transferred (or “dropped”) to the hopper a signal is sent which will release the pack house entities. The pack house entities will be assigned a cartridge size, speed for the KP and amount of cartridges in a box. This assignment is done in a separate logic and though the logic is simple is lengthy in nature. Only a fraction of the assignment logic is shown below.
Once the entities are assigned its attributes the cartridges will be produced. The tank will be emptied according to the assigned rate and will continue until the weight of the cartridge has been reached. The entities will keep rerunning the cycle. At the end of the cycle the entities will split in two for the original entity to rerun the cycle and the clone to move on to the batching and boxing phase of the model. Once enough entities are batched to form a box they will leave the system. The pack house logic includes logic for determining if a changeover is required, or if a new order can start being processed should the size remain the same.

This model is the same for B1, B2 and B8.
10. Simulation
The verified model for B1, B2 and B8 will first be simulated and the data returned will be used as a base for evaluating further simulation results. The second simulation will involve simulating a pack house where the KP’s have been replaced. The new KP’s will be faster (maximum speed of 200 cartridges per minute), thus influencing the tank emptying rate, more reliable and will require half as many wire changes. A final simulation is run with the existing KPs showing no breakdowns but the speed and wire change times remain unchanged.

The data used to run the simulation is included in Appendix A. The data includes all the possible mix types as well as a variety of sizes, which would require the occasional changeover, all in different order sizes (required box count). This data reflects an accurate slice of the plant requirements.
11. Results

11.1. Existing plant setup (B1):
The existing setup for B1 shows that for a simulation run of 480 hours 30,124 boxes can be output for the selected input data.

11.2. Existing plant setup (B2):
The existing setup for B2 shows that for a simulation run of 480 hours 30,124 boxes can be output for the selected input data.

11.3. Existing plant setup (B8):
The existing setup for B8 shows that for a simulation run of 480 hours 29,802 boxes can be output for the selected input data.

11.4. Plant running with new KPs
With the new KPs the wire change occurs only 50% as often as the old plant, the output rate for the tanks have been increased by a factor of 1.66 (new maximum speed of 200 cart/min vs 120 cart/min) and no breakdowns are included. With the same data as the current setup and for a simulation run of 480 hours the plant shows an improvement with an output of 30,314 boxes.

11.5. Plant running with improved KPs
The existing setup for a plant without any breakdowns shows that for a simulation run of 480 hours 30,189 boxes can be output for the selected input data.
12. Analysis

12.1. B1 vs. New KP
Though the new KP shows improvement over the old one the improvement of 190 boxes over 480 hours only shows a 0.63% improvement over the existing setup. The new KP has an improved availability and produces cartridges faster and should rightly show an improvement, but it appears that the KP's currently in use produces cartridges at a sufficient pace. During analysis of the system the true bottleneck of the system was found to be the mixing process for all sizes larger than 29x270 and the simulation proves this conclusion. Only for sizes smaller than this will the new KP show any significant improvement.

12.2. B2 vs. New KP
For B2 a new KP shows an improvement of 190 boxes equating to 0.63% overall improvement. These results are comparable to B1’s results. Whether or not this improvement is significant is a decision for management.

12.3. B8 vs. New KP
B8 shows the most improvement to be gained by replacing the KP. A new KP shows an improvement of 512 boxes equating to 1.7% overall improvement. Whether or not this improvement is significant remains a decision for management.

12.4. Plant without breakdowns vs. New KP
A plant without and breakdowns shows an improvement of 125 boxes with a new KP, equating to 0.4% overall improvement. This simulation shows the influence of the mix bottleneck on the plant and shows that despite breakdowns B1 operates close to the maximum plant output.
1. Conclusion
Availability directly influences the reliability of a plant and its ability to fulfil orders on short notice. A plant that struggles with availability will not be a very flexible plant and will almost constantly struggle to catch up. If availability is to be improved an enhanced maintenance plan and complete machine overall of the existing KP’s is rather recommended than simply replacing the KPs. The decision to replace the KPs rather than maintain the existing KPs is purely an economical choice and should be made on the basis of available capital and long term maintenance cost. Turnover time for orders filled is generally 1 day and a lengthy breakdown on certain KPs (such as B2’s KPS which are the only KPs to produce sizes larger than 50mm in diameter) can prove to be disastrous. Improvement or replacement of these KPs should be a first priority.

Currently the demand for product is greater than the output of the plant. Lengthening the shift hours proved to be effective in temporarily increasing the plant output, but a long term solution proves to be more difficult than initially thought and simulation shows that a faster KP will not solve the problem. To improve the plant’s production the focus needs to shift to the true bottleneck, which is the mix time for all sizes larger than 29x270mm.
2. Summary

Simulation is but one tool in the belt of the industrial engineer. The degree of ease with which the effect of possible changes can be seen both in machines and management philosophy is invaluable and has the potential to save a fortune. With this simulation the advantage of simulation and the effectiveness as a tool for the Industrial Engineer can clearly be seen.
3. References


Appendix A

Input data for the simulation:

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