MODELLING AND OPTIMIZATION OF EURYCOMA LONGIFOLIA WATER EXTRACT PRODUCTION

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Eurycoma longifolia or Tongkat Ali water extract is a valued product in the phytochemical industry. This work features the modelling and optimization of a Tongkat Ali water extract production using SuperPro Designer®, a commercial batch process simulator. The objective of this work is to design an economically viable production scheme for a locally developed Tongkat Ali extract production process. The current pilot scale production scheme with an annual production rate of 390 kg of Tongkat Ali extract was used to simulate the base case process. Four alternative production schemes were further developed with several debottlenecking and optimization strategies. The final alternative scheme was reported to achieve a product yield of 3.00%, with an annual production of 1137.72 kg of Tongkat Ali extract. The minimum batch cycle time was reduced from 24.44 h in the base case to 8.32 h. Economic analysis determined that the proposed alternative production scheme has an annual revenue of $6.32M, with a 86% gross margin and a 55% return on investment (ROI). The payback period of this scheme was estimated to be less than two years.

Keywords: phytochemical processing; process simulation; optimization; batch processes; process debottlenecking; economic analysis.

INTRODUCTION

Eurycoma longifolia or more commonly known as Tongkat Ali, is a tropical herbal plant found in several parts of South East Asia such as Malaysia, Indonesia, and Vietnam. Locally it is also known as Payung Ali, Penawar Pahit, Setunjang Bumi, Bedara Pahit, Tongkat Baginda, Pokok Syurga, Tongkat Ali Hitam, Pokok Jelas and Jelaih. There are four different species of Tongkat Ali plant, namely Eurycoma longifolia, Eurycoma apiculata, Polyalthia bullata and Goniothalamus sp. (Aziz et al., 2003). Among the four, Eurycoma longifolia is the most commonly used species for the extract production. This plant bears fruit after 2½ years of cultivation while the root is usually taken to be processed after 4 years of cultivation.

Traditionally, Tongkat Ali is used for its aphrodisiac, anti-pyretic and anti-malarial effects as well as a general tonic (Kuo et al., 2003). A decoction of its long woody tap root is taken orally. The benefits of the roots of Tongkat Ali include restoring energy and vitality, enhancing blood flow and functioning as a herbal ingredient for women after child birth (Ismail et al., 1999). The leaves cure malaria, ulcers, syphilis and gonorrhea, prevents gum diseases, and relieves insect bites (Adenan, 2003).

The herbal-based phytochemical industry is a new and upcoming industrial sector in Malaysia. Common phytochemicals or herbal products in the market include Tongkat Ali, Misai Kucing (Orthosiphon stamineus) and Hempedu Bumi (Andrographis paniculata) extracts. Misai Kucing can be used for kidney related and joint ailments while Hempedu Bumi is used for its anti-diabetic and anti-hypertensive properties (Aziz et al., 2003). Due to the high market demand and their medicinal effects, these phytochemical products have a high commercial value in the local and global market (Aziz et al., 2003). For instance, Tongkat Ali water extracts can be sold for up to USD26 per bottle of 60 capsules, which is equivalent to USD8700/kg extract (Kaur et al., 2003).

However, a common pitfall associated with this industrial sector is that the production of these phytochemicals (such as Tongkat Ali water extract) is mainly carried out through various traditional methods (e.g., boiling or soaking) which often lead to high losses and low product yield. Hence more effort is needed to develop this ‘backyard’ industry into a viable and profitable industrial sector. Various engineering contribution and practices are needed for this transformation. This includes the various
stages of phytochemical processing, e.g., planting and harvesting, raw material preparation, processing as well as value added production (Aziz et al., 2005). Engineering practices such as processing (extraction) technology, process synthesis and optimization, and product formulation hence play important roles in ensuring the ‘modernization’ of phytochemical industry to be successful (Aziz et al., 2005).

This work presents the use of a batch process simulator in modelling and optimizing a locally developed process for Tongkat Ali water extract production. It aims to develop an economically viable production scheme via the use of computer aided process design (CAPD) and simulation tools. CAPD and simulation are important tools in the process industries since the late 1960s. It involves the use of computers to perform steady-state heat and mass balancing and costing calculations for a process (Westenberg et al., 1979). However, this tool is still relatively new to the field of bio-related process engineering (Shanklin et al., 2001), such as that in the biochemical and phytochemical industries. Works on bio-related process modelling and simulation were only found in the last decade (Petrides, 1994; Petrides et al., 1995; Ernst et al., 1997; Evangelista et al., 1998; Rouf et al., 2001).

In this work, SuperPro Designer® v6.0 (Intelligen, 2005), a commercial process simulation tool, is used to develop an economically viable scheme for the production of Tongkat Ali water extract. SuperPro Designer® is a window-based simulation software for modelling biochemical, food, pharmaceutical, specialty chemical, as well as other continuous and batch manufacturing processes. The base case simulation model is based on the current operating condition of a pilot scale production at Chemical Engineering Pilot Plant, Universiti Teknologi Malaysia (CEPP, UTM). To achieve industrial scale production, it is important to consider the various process and scheduling bottlenecks in the current production setup. Four alternative production schemes were further developed in the simulation model by incorporating various debottlenecking strategies to overcome the current process limitations. Value added steps were introduced to produce a final Tongkat Ali extract product of higher commercial value. Results reveal that the industrial scale production scheme is of good economic performance, with a return on investment (ROI) figure of 55% and a payback period of approximately two years.

**PROCESS DESCRIPTION**

Figure 1 shows the process flow diagram of a pilot scale production of *Eurycoma longifolia* water extract developed and operated at CEPP, UTM. The two main processing steps in this water extract production consists of the two stage counter-current solid–liquid extraction (leaching) process as well as the spray drying operation. The current process is operated at a batch throughput of 40 kg of ground Tongkat Ali root, which is supplied in chip form. The processing steps are explained in detail as follows.

In the first operating step, the two stage counter-current solid–liquid extraction process, fresh ground Tongkat Ali root chips are sent to the extraction vessel to be extracted using the solvent of boiled water. The ratio of water volume to the root chips weight is maintained at 6 L: 1 kg. In the first stage of extraction, Tongkat Ali roots are boiled with fresh water (or recycled water for the second batch and above) at a temperature range of 110–120°C. This boiling operation is maintained for 2 h to provide sufficient time for the phytochemicals in the root chips to be leached into the extraction solvent (water).

Upon the completion of the first stage of extraction the extracted liquid is pumped and stored in a holding tank to be later sent for spray drying. The leftover chips are then extracted again using fresh solvent in the second stage of extraction with the same operating conditions as the first extraction stage. Upon the completion of the second stage extraction the solvent is removed and stored for reuse in the following batch and the leftover chips are discharged. Approximately 35% of the solvent (water) is absorbed in the discharged chips and this is taken as process losses.

The extract from the first extraction stage is sent to the spray dryer operated at 170°C to produce Tongkat Ali extract powder. Due to the limitation of the spray drier capacity (a feed rate of 7 L h⁻¹ of spray liquid), the drying operation takes approximately 22 h to complete. Spray drying is widely used in most herbal-based phytochemical processing to produce extract powders, mainly due to its relatively shorter process time and lower process economics, as compared to other product drying techniques such as freeze drying. In the current production scheme, the spray dried extract powder is sold as the final product in bulk form.

In this pilot scale production, the overall process yield of Tongkat Ali extract is estimated at 3.0 wt%. A detailed simulation has been performed to model the production and to assess the annual process throughput as well as its economic performance, as described in the following section.

**BASE CASE PROCESS SIMULATION**

In the development of the base case simulation model (Figure 2), user-defined components were approximated within the simulator database due to the absence of Tongkat Ali substances in the simulator component database. This includes the Tongkat Ali root chips, fibre, residue and extract. Due to the nature of the process that is operated in batch mode, the base case simulation model was developed to reflect the actual operating condition of the process. In the modelling environment of SuperPro Designer®, this involves the modelling of a few operations that take place sequentially in a single unit procedure (Intelligen, 2005). For instance, vessel procedure P-1 in the Extraction section of Figure 2 was used to model the first stage of extraction process that consists of sequential operations of raw material charges, material heating, extraction process as well as product discharge. All these individual operations took place in the single vessel of V-101. The modelling of these single operations is described next.

The first operation in P-1 involves the charging of the raw material, i.e., 40 kg of ground Tongkat Ali root chips (denoted as ‘TA root’ in Figure 2) into the extraction vessel. Extraction solvent charging is the next subsequent operation in the procedure. As mentioned earlier, the solvent for the first extraction stage mainly consists of the recycle water (denoted as ‘R.water’) from the second stage of the extraction process. After the transferring of recycle water has taken place, 30 L of fresh water is next charged into P-1 as solvent make-up, to supplement the losses of
recycle water in the solid residue from the extraction process. The operation that follows is the heating of solvent-root mixture from room temperature to 110°C. The extraction process was assumed to take place at the beginning of the heating operation. The extraction vessel was maintained at 110°C for 2 h. Based on the product yield of 3.0 wt% in the pilot scale operation, Tongkat Ali extract produced in the extraction vessel was determined as 1.2 kg per batch of extraction operation.

Upon the completion of the extraction process, the resulting extract-water and solid mixture was sent to the centrifugation procedure P-2, that took place in the Bowl Centrifuge BC-101. This procedure is used to model the siphon system in the current pilot plant production scheme for the removal of wood chips from the effluent of extraction vessel V-101. In modelling the centrifugation procedure P-2, complete removal is set for the Tongkat Ali fibre (denoted as ‘TA fibre’); while 35% removal for extract–water mixture to represent the product losses. The remaining extract–water mixture (denoted as ‘Ext. water’) is transferred to be temporarily stored in the storage procedure P-5 (in vessel V-103 in Drying section).

![Process flow diagram of pilot scale Tongkat Ali water extract production.](image1)

**Figure 1.** Process flow diagram of pilot scale Tongkat Ali water extract production.

![Simulation flowsheet for base case process.](image2)

**Figure 2.** Simulation flowsheet for base case process.
The separated solids from P-2 are transferred into vessel procedure P-3 (in V-102) to undergo the second stage of the extraction process. The operating condition for the second stage of the extraction process is the same with that in the first stage in procedure P-1. Note that due to the counter-current mode of extraction process, 240 L of fresh water is fed at this second stage of extraction process. Product yield at this stage is assumed at 1%. The effluent from vessel procedure P-3 is separated by the centrifugation procedure P-4, which utilizes the same equipment of BC-101 in procedure P-2. The extract water leaving P-4 is recycled to P-1 (in stream ‘R.water’) while the solid content leaves as process residue. The operating parameter for this procedure was also set to be the same with that in procedure P-2.

Upon the completion of extract mixture transfer-in operation of P-5, the stored extract–water mixture is sent to the spray drying procedure (P-6/SDR-101) at a flowrate of 0.12 L min$^{-1}$ (equivalent to a feed rate of 7.1 L h$^{-1}$ of spray liquid). Ambient air is heated to 170 °C before it is fed into SDR-101 as the drying medium. Hot air and evaporated water vapor is emitted from the top stream of SDR-101 while TA powder leaves at the bottom stream at 70°C. It is assumed that 1% of the Tongkat Ali extract is lost together with the emitted air. Upon the completion of the spray drying operation, spray dryer SDR-101 undergoes a cleaning-in-place operation, which is the last operation for the complete batch recipe for the Tongkat Ali extract production.

As the manufacturing process is carried out in batch operation, efforts have been made to document the scheduling details of each processing steps. This includes the setup time, process time, and start time of each individual operation in each unit procedure. Setup time (SUT) is the preparation time needed before an operation takes place. Often, this involves the loading of raw material (e.g., from loading area), equipment preparation or setup that often occur in batch processing. Process time (PT), on the other hand, represents the actual processing duration needed for each operation. Finally, start time (ST) documents the beginning of an operation. The details of this scheduling summary are shown in Table 1, with the Operation Gantt Chart shown in Figure 3.

Note that the process time for certain operations are dependant upon other operations of the same or the opposite procedure. In SuperPro Designer® inter-dependency of operation durations is termed as the Master–Slave Relationship (Intelligen, 2005). For example, the transfer in operation of recycle water (R. water) in procedure P-1 (termed as the slave operation) is set to follow the duration of centrifugation operation in procedure P-4 (termed as master operation).

Process throughput analysis is next performed on the base case simulation model. The model reports an overall product yield of 3.02%, with the batch production of 1.21 kg Tongkat Ali extracts. Based on the annual operating time of 7920 h and minimum cycle time of 24.44 h, the annual production for the process model is calculated as 323 batches. This corresponds to 390.73 kg of Tongkat Ali extract produced per annum. Currently this production rate is not sufficient for present local demand and increasing international orders.

Preliminary economic analysis is also conducted on the base case model. The raw material price for the case study includes the Tongkat Ali root chips purchased at a price of $6.55/kg and fresh water supplied at 0.06 cent/kg while the final product of bulk Tongkat Ali powder is sold at a price of $660/kg. Results reveal that the current production scheme has relatively high capital (assuming that all process equipment are newly purchased) and operating cost (a break down of annual operating cost is shown in Table 2) as compared to its annual revenue. A negative value is reported for gross margin of the model and its return on investment (ROI) is as low at 5.35% compared to the minimum preferred ROI value of 30%. Hence efforts are needed to improve the economic performance of the production scheme for a more economically viable production.

**BOTTLENECK IDENTIFICATION STRATEGIES**

In order to increase the process throughput, one will have to identify the process bottleneck that limits the current production. Bottlenecks are process limitations that are related to either equipment or resource such as demand for various utilities, labour, raw material, and so on. In batch manufacturing, two types of process bottlenecks can be identified, i.e., size bottleneck and scheduling bottleneck.

Similarly, for batch processes, equipment utilization can be measured through its capacity utilization and equipment uptime (Koulouris et al., 2000; Petrides et al., 2002). Capacity utilization is defined as the fraction of equipment’s capacity used during an operation while equipment uptime is the measure of how effective a piece of equipment is utilised in time. The product of equipment capacity utilization and its uptime defines the combined utilization of the respective equipment. This measures how certain equipment utilised its capacity (size) and uptime (Koulouris et al., 2000; Petrides et al., 2002). The processing step with the highest combined utilization is in general the first candidate equipment to become process bottleneck.

Figure 4 shows the Throughput Analysis Chart that displays capacity utilization, equipment uptime and combined utilization for each procedure/equipment pair. As shown, the spray drying procedure (P-6/SDR-101) is identified as the process bottleneck due to its highest combined utilization. The capacity utilization of this procedure has reached its maximum of 100% (due to the limitation of its feed flowrate of 0.12 L min$^{-1}$); while its equipment uptime is relatively high (drying operation duration of 22.11 h, Table 1). P-6 can also be classified as the process scheduling bottleneck which limits the annual production of 323 batches per year. Hence, in order to increase the annual production, debottlenecking strategies should focus on the reduction of the drying operation time which will enable more batches to be produced annually.

**DEBOTTLENECKING SCHEMES TO INCREASE PRODUCTION AND IMPROVE PROFITABILITY**

The previous section determined that the current production of Tongkat Ali extract powder is economically infeasible due to the low revenue generated by the low annual production rate. However efforts to increase production were limited by the process scheduling bottleneck, i.e., spray drying procedure of P-6/SDR-10. Three
Table 1. Scheduling summary for base case model.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Operation</th>
<th>Process scheduling</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-1/V-101</td>
<td>Charge TA root (CHARGE-TA)</td>
<td>SUT = 10 min</td>
<td>Preparation of Tongkat Ali root chips from storage, Manual charging</td>
</tr>
<tr>
<td></td>
<td>Transfer in R.water (TRANS-IN-R.H2O)</td>
<td>PT = based on mass flowrate of 2.5 kg min⁻¹</td>
<td>Pipe fixing and to avoid overlapping, R.water recycle stream fed from P-4</td>
</tr>
<tr>
<td></td>
<td>Charge in fresh water (CHARGE-H2O)</td>
<td>ST = after CHARGE-TA ends</td>
<td>Pipe fixing, manual start-up, Fresh water charge in as make-up solvent</td>
</tr>
<tr>
<td></td>
<td>Heat (HEAT-1)</td>
<td>PT = based on volumetric flowrate of 4.8 L min⁻¹</td>
<td>Manual start-up, Final temperature = 110°C</td>
</tr>
<tr>
<td></td>
<td>Extraction (EXTRACT-1)</td>
<td>ST = after CHARGE-H2O ends</td>
<td>First stage of counter-current leaching process, Leaching is assumed to start when the root chips contact with solvent</td>
</tr>
<tr>
<td></td>
<td>Transfer out extraction mixture (TRANS-OUT-1)</td>
<td>PT = Master-slave Relationship with P-2</td>
<td>Pipe fixing, manual start, Extraction mixture is transferred to P-2</td>
</tr>
<tr>
<td>P-2/BC-101</td>
<td>Solid liquid separation (CENTRIFUGE-1)</td>
<td>SUT = 10 min</td>
<td>Manual start-up</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PT = 2 h</td>
<td>Solid separation from P-1 effluent</td>
</tr>
<tr>
<td>P-3/V-102</td>
<td>Transfer in TA fibre (TRANS-IN-TA-FIBRE)</td>
<td>SUT = 10 min</td>
<td>Manual start-up</td>
</tr>
<tr>
<td></td>
<td>Charge in fresh water II (CHARGE-H2O)</td>
<td>ST = starts with TRANS-OUT-1 in P-1</td>
<td>Separated solid is transferred from P-2</td>
</tr>
<tr>
<td></td>
<td>Heat (HEAT-1)</td>
<td>PT = Master-slave Relationship with P-2</td>
<td>Fresh solvent is fed</td>
</tr>
<tr>
<td></td>
<td>Extraction (EXTRACT-1)</td>
<td>ST = after CHARGE-H2O ends</td>
<td>Manual start-up</td>
</tr>
<tr>
<td></td>
<td>Transfer out extraction mixture (TRANS-OUT-1)</td>
<td>PT = Master-slave Relationship with P-4</td>
<td>Second stage of counter-current leaching process</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ST = after EXTRACT-1 ends</td>
<td>Extraction mixture is transferred to P-4</td>
</tr>
<tr>
<td>P-4/BC-101</td>
<td>Solid liquid separation (CENTRIFUGE-1)</td>
<td>SUT = 10 min</td>
<td>Manual start-up</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PT = 2 h</td>
<td>Solids separation from P-3 effluent</td>
</tr>
<tr>
<td>P-5/V-103</td>
<td>Transfer in Ext. water (TRANS-IN-1)</td>
<td>SUT = 10 min</td>
<td>Manual start-up</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PT = Master-slave Relationship with P-2</td>
<td>Extract-water transfer from P-2</td>
</tr>
<tr>
<td></td>
<td>Temporary storage (STORE-1)</td>
<td>PT = 2 h</td>
<td>Stores liquid for P-6 feed</td>
</tr>
<tr>
<td></td>
<td>Transfer out storage product (TRANS-OUT-1)</td>
<td>SUT = 20 min</td>
<td>Manual start-up</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PT = based on volumetric flowrate of 0.12 L min⁻¹</td>
<td>Based on the feed flowrate of P-6</td>
</tr>
<tr>
<td>P-6/SDR-101</td>
<td>Spray drying (DRY-1)</td>
<td>SUT = 20 min</td>
<td>Manual start-up</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PT = 22.11 h</td>
<td>Production of Tongkat Ali extract powder</td>
</tr>
<tr>
<td></td>
<td>Chamber cleaning (CIP-1)</td>
<td>PT = 15 min</td>
<td>Cleaning of SDR-101</td>
</tr>
</tbody>
</table>
debottlenecking schemes were developed based on the base case simulation. These schemes were analysed to evaluate their viability to increase the plant annual production. Economic evaluation was also performed to evaluate all debottlenecking schemes to identify the most economically attractive option.

**ALTERNATIVE DEBOTTLENECKING SCHEMES**

In Scheme 1 (Figure 5), a new spray drying procedure (P-8/SDR-102) was added in parallel with the existing spray dryer (P-7/SDR-101) to reduce the process time for spray drying operation by half. The process time of spray drying operation was reduced significantly from 22.11 h to 11.05 h while other equipment and scheduling setup remained unchanged. The losses of Tongkat Ali extract in both spray drying procedures were assumed to remain at 1%.

Scheme 2 adds a new double effect forward feed evaporator (P-6/EV-101) to concentrate the water extract prior to the spray dryer (Figure 6). Due to the reduction of volume in the Tongkat Ali water extract, the process time for the spray drying operation is assumed to reduce by half, i.e., from 22.11 h to 11.05 h. Operating conditions for all other unit procedures remain unchanged.

Table 3 shows the process throughput and economics summary of the three debottlenecking schemes as compared to the base case simulation model. All debottlenecking schemes demonstrate significant improvement on the annual production. This is mainly due to the reduction of minimum cycle time associated with spray drying procedures. Note that Scheme 2 and Scheme 3 exhibit lower value of overall product yield due to additional losses in the evaporator (P-6/EV-101). Among all schemes, Scheme 3 has the highest annual production and hence identified as the debottlenecking strategy. However economic analysis of the proposed schemes reveals that these three schemes are still economically infeasible as the ROI values are still well below the desired 30% although the annual throughput has been increased.
All proposed schemes have seen an increase in capital and operating costs due to addition of new equipments. As shown in Table 3, the operating cost for all the debottlenecking schemes are higher than the total revenues. This leads to the low ROI values and therefore a payback period for all schemes is unachievable. The main reason for this defect is the low revenue of the final product. Therefore, in the final scheme proposed, Scheme 4, alternatives to produce a value-added product are implemented.

Attention is given on efforts to reduce process operating cost and to add value to the final product.

**Economic Optimization Scheme**

The first effort in Scheme 4 (Figure 8) is to reduce the raw material cost of the process by adding a new grinder (P-1/GR10) in the Extraction section. Raw material in the base case simulation is taken as the ground Tongkat Figure 4. Throughput Analysis Chart for base case simulation.

Figure 4. Throughput Analysis Chart for base case simulation.

Figure 5. Simulation flowsheet of debottlenecking Scheme 1.

Ali wood chips with a cost of $6.55/kg. With the addition of a grinder, the raw material can be substituted with fresh Tongkat Ali roots which cost $3.20/kg, approximately half of the original cost.

Effort is next made to improve the process economics by producing a value-added final product. In all previous proposed schemes, the final product of Tongkat Ali extract powder is sold at a price of $660/kg. An alternative to
produce a higher value-added product is the Tongkat Ali extract capsules which are sold at a price of $26 per bottle of 60 capsules, which is equivalent to $8700/kg of Tongkat Ali extract. To produce Tongkat Ali extract capsules, new equipment are needed in the Packing section. As shown in Figure 8, the newly added equipment include the procedures of capsule mixture preparation (P-12/MX-102), capsuling (P-13/TB-101), bottling (P-14/BX-101) and boxing (P-15/BX-102).

The Tongkat Ali extract powder from the spray dryers is mixed with the filler of Maltodextrin, an easily digestible carbohydrate made from natural corn starch (user-defined component, purchase cost: $1.50/kg) in procedure P-12/MX-102 at a ratio of 1 kg extract:8 kg Maltodextrin. The
The final product of Scheme 4 is no longer Tongkat Ali extract powder but extract capsules in a bottle packed in boxes. The total capital and operating cost has increased in Scheme 4 due to the installation of new grinding and packaging equipment as shown in Table 3. However, this increase is justified by a drastic increase in the process revenues. This fulfils the objective to increase the total revenues with higher margin. As a result of the increase in revenues the gross margin and ROI have improved significantly. In the previous schemes calculations show that the capital investment was not recoverable since the operating cost exceeded the total revenues. If this scheme is implemented the capital investment can be recovered in 1.82 years with a ROI of 55%. Table 4 shows the main specifications and purchase cost of equipment utilised in Scheme 4, excerpted from the software SuperPro Designer®. Note that the purchase cost of these equipment is based on the local quoted rate. Also, the unlisted equipment (e.g., pumps, valves, and so on) cost is assumed to be 20% of the major equipment cost.

The scheduling summary for Scheme 4 can be shown in Operation Gantt Chart (Figure 9).

CONCLUSION

Tongkat Ali extract production is modelled and optimized in this work based on an existing pilot scale manufacturing setup. The base case process is analysed and the spray drying section is identified as the overall process bottleneck. Three debottlenecking schemes are proposed and analysed through simulation. The debottlenecking scheme with the highest throughput that fulfils the customers’ need is further analysed to assess its economic performance. Due to the unattractive economic performance a new grinder and packaging section were proposed to add value to the final product. The modification yields an annual revenue of $6.3M with a gross margin of 86%, a return on investment of 55% and a payback period of less than 2 years.

REFERENCES


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