Optimization of Urea Solution Tie-in System in The Urea Fertilizer Manufacturing

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Abstract

This paper develops a mathematical economic optimization for urea solution tie-in system in the urea fertilizer plant. The urea solution tie-in system can be used as an effective strategy to increase the urea production and the company revenue as well. The relevant data for the model are obtained from Pupuk Kaltim Fertilizer Company in Indonesia. The mathematical formulation of the model is solved using the General Algebraic Modeling System (GAMS) software. A sensitivity analysis has also been conducted on the optimal solutions of the model. It is concluded that, with the present model, decisions can be made with different strategies and their influence on company revenue. Furthermore, this model will be highly useful for corporate decision making to achieve maximum profit while meeting certain production targets.

Keywords
Modeling, optimization, urea tie-in system, fertilizer, mathematical programming

1. Introduction
Urea (NH_2CONH_2), containing 46% N, is greatly importance to the agriculture industry as a nitrogen-rich fertilizer. Urea is made from the of ammonia with carbon dioxide in a chemical process in the form of a solid urea prill (sizes 1 to 3.35 mm) or granules (size 2 to 4.75 mm). A urea fertilizer plant is a complex engineering system consisting of several systems, i.e., synthesis section, purification section, waste water treatment, and finishing section including urea crystallization and urea prilling / granulating (Meessen and Petersen, 1996). PT Pupuk Kaltim (Pupuk Kaltim) as the biggest urea fertilizer manufacturer in Indonesia currently operates five units of urea plant with total capacity of 3.43 million tons of urea per year. As a company that became the foundation of strategic industries that support National Food Security Program, Pupuk Kaltim always strive to develop every opportunity to make the plant viable for operation. Moreover, the on-stream factor (OSF) of the plant shall be maintained at 100% to prevent loss of revenue during downtime as well as maintaining the reliability level of the plant (O'Connor, 1991). Therefore, an effective strategy needs to be framed out to achieve effective performance and expected urea production while maximizing revenue.

In this paper, the work deals with the modeling and optimization of urea solution (US) tie-in system. The urea solution is a semi-product of the urea plant which will be further processed to produce a solid urea product in the form of prills or granules. The US tie-in system is built in order to maintain the production of urea continuously and the opportunity to increase the production of urea prill or urea granule depending on the selling prices in the market to achieve a high profit margin. Considering of its benefit, the main objective of the present paper is to develop a mathematical economic model for urea solution tie-in system at Pupuk Kaltim fertilizer plant with the aim of optimizing the urea production and the company profit.

2. Modeling framework

2.1 System description

The production of urea involves the combination of ammonia and carbon dioxide in the reactor at high pressure and temperature. The urea is formed in a twostep reaction, which the first step is the reaction between ammonia and carbon dioxide to form ammonium carbamate and dehydration of ammonium carbamate by the application of heat to form urea and water (Dente et al, 1992):

$$2NH_3 + CO_2 \leftrightarrow NH_2COONH_4 \quad (ammonium\ carbamate) \tag{1}$$

$$NH_2COONH_4 \leftrightarrow H_2O + NH_2CONH_2 \quad (urea) \tag{2}$$

The conversion (on a CO2 basis) is usually in the order of 58% - 60% at a pressure of 50 barg. The urea solution as a product of synthesis section is purified from its impurities, i.e., water and unconsumed reactants including ammonia, carbon dioxide, and ammonium carbamate at the purification section. The 68% - 75% of the urea solution from purification section is then concentrated by heating under vacuum to produce 96% - 99% w/w molten urea and to be further processed to form a solid prills or granules depending on the finishing process being used either a prilling tower or a granulator (Ruskan, 1976; Capes, 1980).

Pupuk Kaltim operates five units of urea plant with three different technologies, i.e., Stamicarbon, Snamprogetti, and Toyo ACES-21, with two types of urea products, i.e. urea prill and urea granule. The production capacity and type of product of each plant are described in Table 1.

Table 1. Production capacity of Pupuk Kaltim urea plant

Plant	Product	Production (ton / day)		
		Minimum	Normal	Maximum
1	Prill	1380	1725	2035
2	Prill	1380	1725	1777
3	Granule	1380	1725	1725
4	Granule	1380	1725	1777
5	Granule	2800	3500	3675

All plants are expected to operate effectively in terms of availability and reliability while facing the challenges of the global fertilizer market. In this work, the urea solution tie-in or integration system and its modeling are proposed to handle and convert the urea solution from different plants into products either urea prill or urea granule with high sale profits. The schematic diagram of the US tie-in system is shown in Figure 1. The optimization problem is defined as: determine the optimal utilization of urea solution to produce urea product that generates high profit while achieving the production target and reliability of the plants. The objective function of the optimization formulation is chosen as to maximize the net profit, which can be defined as the difference between the revenue (obtained by selling the products) and cost (operating cost and urea solution cost).

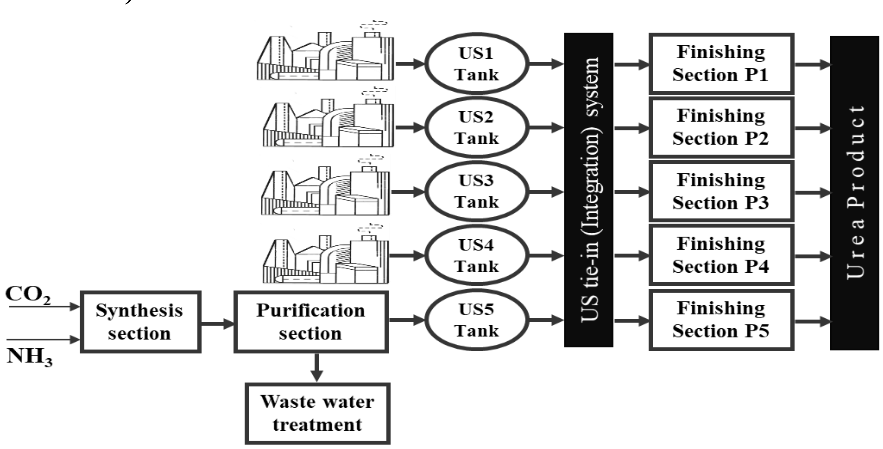

Figure 1. Urea solution tie-in system

2.2 Development of superstructure

A superstructure model is developed for the utilization and conversion of urea solution into products through tie-in or integration system (Figure 2). The developed superstructure consists of five urea solution sources from five urea plants and conversion of US into urea products, where urea prills are produced from Finishing Section at Plant-1/2 and urea granules are produced from Finishing Section at Plant-3/4/5. Numerous utilization of urea solution alternatives to produce urea prill or urea granule are incorporated for achieving the highest profit and optimizing the production target. As presented in Figure 2, three indices are used to represent a processing route of urea solution to produce a solid urea; the first one, *u*, shows the urea solution alternative, *f* shows the finishing section of the urea plant that process urea solution into urea products, and the last one, *p*, shows the finished urea product to be sold.

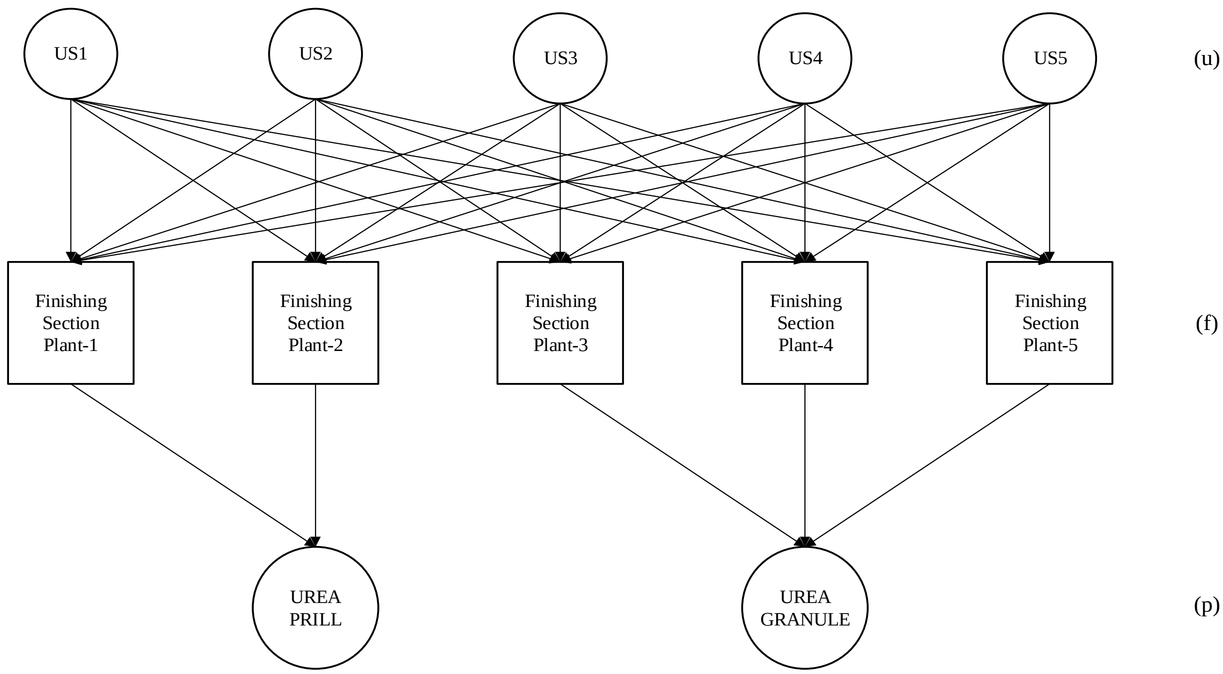

Figure 2. Superstructure for urea solution tie-in or integration management

3. Formulation of optimization model

The superstructure-based optimization model for US tie-in system serves as an effective strategy to achieve maximum profit while meeting certain production targets. Detailed steps about constructing such superstructure are well explained by Murillo-Alvarado et al. (2013), while the purpose of this study is not to discuss such details but rather to present a generalized optimization model that selects the best processing route to produce urea (prills and/or granules) from five urea solution alternatives. The optimization model comprises of mass balance constraints and objective function.

3.1 Mass balance constraints

For each processing route to produce urea prills / granules from urea solution through integration line in the superstructure, the mass balance must be satisfied. Equations for mass balance of urea solution sent to certain urea plant through tie-in or integration line are shown by Eq. (3) and Eq. (4).

$$\sum_u^U TRANS_{u,f,p} = PROC_{f,p} \tag{3}$$

$$\sum_f^F PROC_{f,p} = TARGET_p \tag{4}$$

where $TRANS_{u,f,p}$ is the amount of urea solution *u* to be processed in plant *f* to produce urea *p*. $PROC_{f,p}$ is the amount of the urea product *p* produced from plant *f*. $TARGET_p$ is the production target of urea.

The total production of urea is expected to be more than normal production rate of 8320 ton urea/day while maximizing the net profit as expressed in Eq. (5).

$$\sum_p^P TARGET_p \geq 8320 \tag{5}$$

The upper limit or maximum production of each type of urea product is 3812 ton/day and 7177 ton/day for urea prill and urea granule, respectively.

As mentioned earlier, the five urea plants have different production capacity (Table 1), which makes the availability of urea solution that can be transferred to integration line per day has different value as shown in Table 2.

Table 2. The availability of urea solution

Urea Solution	Availability (ton / day)
US1	2035
US2	1777
US3	1725
US4	1777
US5	3675
Total	10989

From Table 2 and Table 1, the availability of urea solution of each plant represents the maximum capacity of the plant. Thus, the total availability value become the upper limit of total urea solution that can be sent to finishing section of urea plant to produce urea prills / granules (ton/day) as stated in Eq. (6).

$$\sum_u^U \sum_f^F \sum_p^P TRANS_{u,f,p} \leq 10989 \tag{6}$$

For each urea plant, the maximum capacity of the plant becomes the upper limit of urea prill or urea granule production (ton/day) as expressed in Eqs. (7) – (11).

$$PROC_{f=P1,\ p=prill} \leq 2035 \tag{7}$$
$$PROC_{f=P2,\ p=prill} \leq 1777 \tag{8}$$
$$PROC_{f=P3,\ p=granul} \leq 1725 \tag{9}$$
$$PROC_{f=P4,\ p=granul} \leq 1777 \tag{10}$$
$$PROC_{f=P5,\ p=granul} \leq 3675 \tag{11}$$

As represented in Figure 2, if it is desired to produce urea prills, then the urea solution shall be sent to the finishing section at Plant 1 or Plant 2. Meanwhile, the urea granules can be produced by delivering the urea solution to Plant 3, Plant 4, or Plant 5.

Considering the corporate target of urea production, each urea plant shall operate minimum at 80% of the production capacity. By having the US tie-in system, the total production of urea can be increased with certain allocation of urea solution as describe in Table 3.

Table 3. The distribution amount of urea solution

Urea Solution	Distribution	
	Plant	Value
US 1	P1	$\geq$ 1380 ton/day
	P2+P3+P4+P5	$\leq$ 655 ton/day
US 2	P2	$\geq$ 1380 ton/day
	P1+P3+P4+P5	$\leq$ 397 ton/day
US 3	P3	$\geq$ 1380 ton/day
	P1+P2+P4+P5	$\leq$ 345ton/day
US 4	P4	$\geq$ 1380 ton/day
	P1+P2+P3+P5	$\leq$ 397 ton/day
US 5	P5	$\geq$ 2800 ton/day
	P1+P2+P3+P4	$\leq$ 875 ton/day

3.2 Objective function

The optimization model is formulated with an objective function to maximize profit (USD) which is defined by Eq. (12):

$$Profit = Urea\ Sales - Urea\ Cost - US\ Cost \tag{12}$$

Urea sales is given by:

$$Urea\ Sales = \sum_{p}^{P}(PRICE_p * TARGET_p) \tag{13}$$

where $PRICE_p$ is the selling price of product *p* as shown in Table 4.

Table 4. Urea selling price

Urea	Price (USD / ton urea)
Prill	220
Granule	217

In the current formulation, the operating cost is defined as the cost to process the urea solution into urea products at finishing section of urea plant. Urea Cost represents the operating cost which is modeled as:

$$Urea\ Cost = \sum_{f}^{F}\sum_{p}^{P}(PCOST_{f,p} * PROC_{f,p}) \tag{14}$$

where $PCOST_{f,p}$ is the operating cost to produce urea *p* at Plant *f*. The value of typical operating cost for each plant can be seen in Table 5.

Table 5. Operating cost to process urea solution into product at finishing section of each plant

Plant	Cost (USD / ton urea)
1	42.6
2	44.1
3	51.6
4	57.9
5	70.8

The urea solution is previously produced from synthesis section and purification section. Thus, there is a cost to produce urea solution and this cost is taken into account in optimizing the net profit.

$$US\ Cost = \sum_u^U \sum_f^F \sum_p^P (UCOST_u * TRANS_{u,f,p}) \tag{15}$$

where $UCOST_u$ is the cost of urea solution *u* and its value is shown in Table 6.

Table 6. Data for urea solution cost

Plant	Cost (USD / ton urea)
1	99.4
2	102.9
3	120.4
4	135.1
5	165.2

4. Results and discussion

The optimization formulations were executed in General Algebraic Modelling System (GAMS) software using CPLEX as a solver. The optimization results would determine the utilization path of urea solution and portions of urea products whether to be sold as urea prills or as urea granules depending on the economic profitability. Table 7 tabulates the optimum distributions of urea solution to be processed at certain urea plant and Table 8 shows the optimum production of urea prill and urea granul. The maximum profit obtained in this optimization is USD 117,322,920.00 per year (Table 9).

As shown in Table 7 and Table 8, with the price of urea prill is higher than urea granule (Table 4), to achieve a maximum profit, a total of 10114 ton/day of urea is produced where most of urea plants, i.e., P1, P2, P3, and P4 are operated at their maximum production rate and only P5 is operated at its minimum rate. The maximum production rate of the plant is not only achieved by using its own urea solution but also by utilizing the urea solution from other plants. The values of operating cost and the urea solution cost are factors that determine the utilization of urea solution in the modeling to achieve the optimal economic benefits with a given selling price for urea products.

Table 7. Results of optimal distribution of urea solution

Urea Solution	Plant				
	P1	P2	P3	P4	P5
US1	1638	52	345	-	-
US2	-	1380	-	397	-
US3	-	345	1380	-	-
US4	397	-	-	1380	-
US5	-	-	-	-	2800
Total	2035	1777	1725	1777	2800

Table 8. Results of optimal urea production

Plant	Urea Product	
	Prill	Granule
P1	2035	-
P2	1777	-
P3	-	1725
P4	-	1777
P5	-	2800
Total	3812	6302

Table 9. Result of optimized profit

Products (ton/day)	Urea Prill	Urea Granul	Total Product
	3812	6302	10114
Optimized Profit (USD/year)	117,322,920.00		

Note: 1 year = 330 days of plant operation

Furthermore, the result of optimization also shows that 875 ton of US5 is not utilized and kept in the US tank. This urea solution can be an alternative raw material to produce NPK fertilizer by delivering it through a future connection (Figure 3) from US tie-in or integration line to Pupuk Kaltim NPK fertilizer plants which have a total production capacity of 350 thousand tons per year.

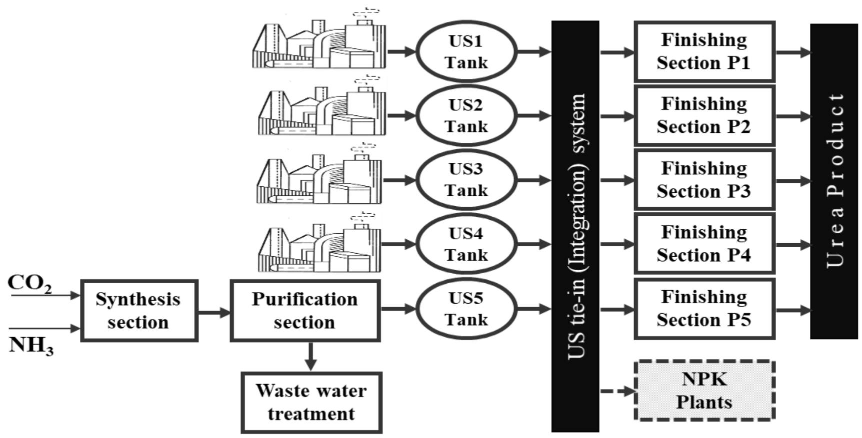

Figure 3. Urea solution tie-in system with future connection to NPK plants

4.1 Sensitivity analysis

Sensitivity analysis is carried out to investigate the influence of key economic on the net profit obtained. The evaluated parameter of the sensitivity analysis in this study is the price of urea prill and urea granule. The sensitivity analyses are conducted by varying both prices incrementally with two cases, i.e., varying the price of urea prill while the urea granule price remains constant and vice versa, to examine their effects on the optimal results (net profit and optimum production of urea prills and urea granules). For Case-1, the selling price of urea prill is increased from USD 130 to USD 220 (USD 30 increment) per ton urea with the price of urea granule is constant at USD 217 per ton urea. In Case-2, the urea prill selling price remains constant at USD 220 per ton urea while the urea granule price is increased incrementally from USD 167, USD 187, USD 217, and USD 247 per ton urea. In addition, the operating costs of each plant and the urea solution costs are kept constant.

Net profit is found to be sensitive to the selling price of urea either urea prill and urea granule as shown in Figure 4 and Figure 5. By increasing the price of urea prill on Case-1 (Figure 4), the production of urea prill is in its maximum rate to achieve the maximum profit. Since the selling price of urea granule remains constant, the optimum production of urea granule will be decreased to obtain a higher margin of profit due to the operating cost of urea granule plants is higher than urea prill plants. The increase of urea prill production is achieved by maximizing the urea production at Plant 1 rather than Plant 2, because Plant 1 has a lower operating cost compared with Plant 2. Meanwhile, since the operating cost of Plant 5 is higher than other urea granule plants, a decrease in total urea granule production will decrease the production rate of Plant 5.

For Case-2, an increase in the selling price of urea granule with constant price of urea prill will affect the production of urea where the total production of urea granule is increased and the total production of urea prill remains constant at its maximum rate (3812 ton). This is because the operating cost of urea prill plants (P1 and P2) is lower than urea granule plants (P3, P4, and P5). Therefore, maximizing the production of urea prills shall be done first by the model before increasing the production of urea granules to improve the net profit.

Furthermore, the optimum distribution of urea solutions to be processed into urea products can be seen in Table 10 to Table 17. The optimal results in Table 10-17 indicate that the net profit is found to be high if the selling price of granule is higher than urea prill price. With a greater total production capacity of urea granule and considering the urea solution produced from urea prill plants (P1 and P2) have a lower cost compared with the US from granule plants (P3, P4, and P5), the model will optimize the distribution of the available urea solution from urea prill plants by delivering it to the urea granule plants for the sake of economic benefits especially when the profit margin of urea prill sales is very low.

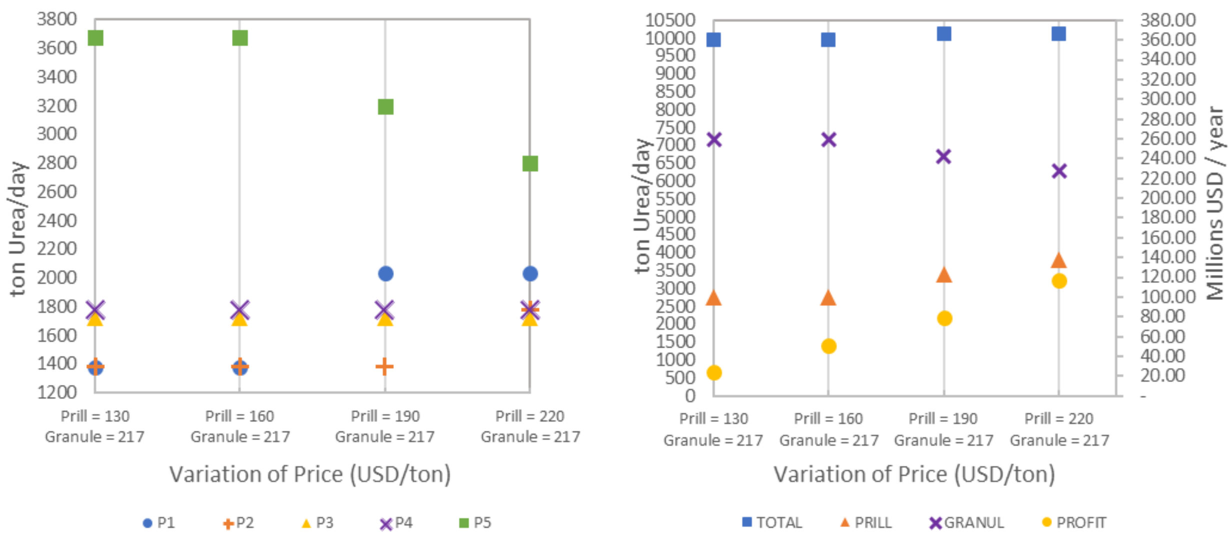

Figure 4. Case 1 – Effect of urea prill selling price increases on production of urea and profitability

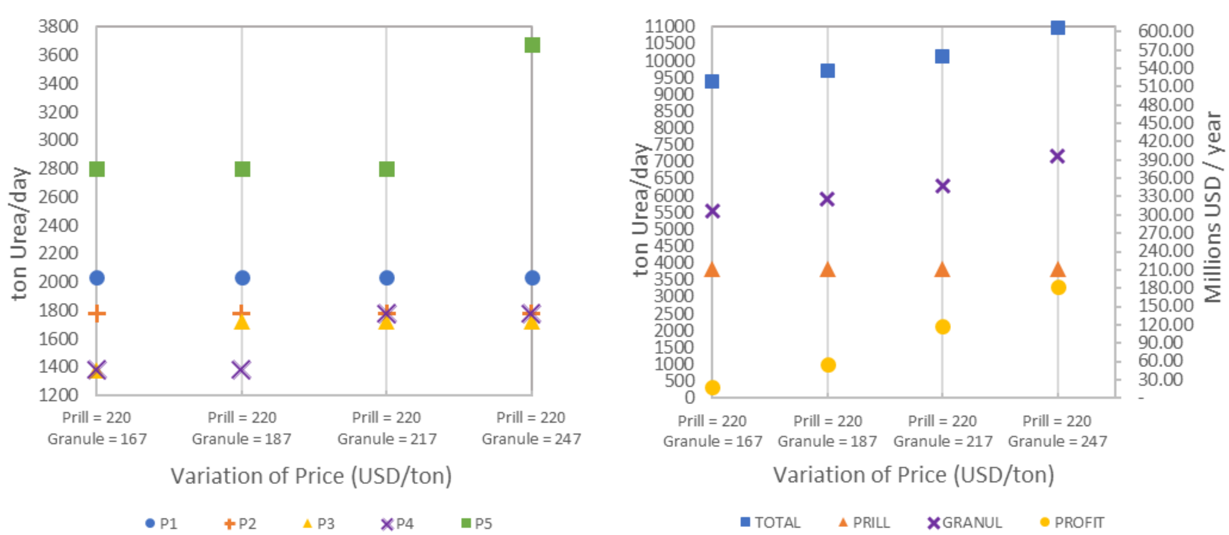

Figure 5. Case 2 – Effect of urea granule selling price increases on production of urea and profitability

Table 10. Optimal distribution of US with urea prill price = 130 USD/ton and urea granule price = USD 217/ton

Urea Solution	Plant				
	P1	P2	P3	P4	P5
US1	1380	-	-	-	655
US2	-	1380	-	177	220
US3	-	-	1505	220	-
US4	-	-	220	1380	-
US5	-	-	-	-	2800
Total	1380	1380	1725	1777	3675
Profit (USD/year)	24,067,692.00				

Table 11. Optimal distribution of US with urea prill price = 160 USD/ton and urea granule price = USD 217/ton

Urea Solution	Plant				
	P1	P2	P3	P4	P5
US1	1380	-	-	-	655
US2	-	1380	-	177	220
US3	-	-	1505	220	-
US4	-	-	220	1380	-
US5	-	-	-	-	2800
Total	1380	1380	1725	1777	3675
Profit (USD/year)	51,391,692.00				

Table 12. Optimal distribution of US with urea prill price = 190 USD/ton and urea granule price = USD 217/ton

Urea Solution	Plant				
	P1	P2	P3	P4	P5
US1	1380	-	258	-	397
US2	-	1380	-	397	-
US3	258	-	1467	-	-
US4	397	-	-	1380	-
US5	-	-	-		2800
Total	2035	1380	1725	1777	3197
Profit (USD/year)	79,623,390.00				

Table 13. Optimal distribution of US with urea prill price = 220 USD/ton and urea granule price = USD 217/ton

Urea Solution	Plant				
	P1	P2	P3	P4	P5
US1	1638	52	345	-	-
US2	-	1380	-	397	-
US3	-	345	1380	-	-
US4	397	-	-	1380	-
US5	-	-	-	-	2800
Total	2035	1777	1725	1777	2800
Profit (USD/year)	117,322,920.00				

Table 14. Optimal distribution of US with urea prill price = 220 USD/ton and urea granule price = USD 167/ton

Urea Solution	Plant				
	P1	P2	P3	P4	P5
US1	1638	397	-	-	-
US2	397	1380	-	-	-
US3	-	-	1380	-	-
US4	-	-	-	1380	-
US5	-	-	-	-	2800
Total	2035	1777	1380	1380	2800
Profit (USD/year)	17,315,430.00				

Table 15. Optimal distribution of US with urea prill price = 220 USD/ton and urea granule price = USD 187/ton

Urea Solution	Plant				
	P1	P2	P3	P4	P5
US1	1380	310	345	-	-
US2	310	1467	-	-	-
US3	345	-	1380	-	-
US4	-	-	-	1380	-
US5	-	-	-	-	2800
Total	2035	1777	1725	1380	2800
Profit (USD/year)	55,719,180.00				

Table 16. Optimal distribution of US with urea prill price = 220 USD/ton and urea granule price = USD 217/ton

Urea Solution	Plant				
	P1	P2	P3	P4	P5
US1	1638	52	345	-	-
US2	-	1380	-	397	-
US3	-	345	1380	-	-
US4	397	-	-	1380	-
US5	-	-	-	-	2800
Total	2035	1777	1725	1777	2800
Profit (USD/year)	117,322,920.00				

Table 17. Optimal distribution of US with urea prill price = 220 USD/ton and urea granule price = USD 247/ton

Urea Solution	Plant				
	P1	P2	P3	P4	P5
US1	1380	-	-	-	655
US2	-	1380	177	-	220
US3	-	177	1548	-	-
US4	177	220	-	1380	-
US5	478	-	-	397	2800
Total	2035	1777	1725	1777	3675
Profit (USD/year)	182,888,970.00				

5. Conclusions

The urea solution tie – in or integration system has an important role in integrating the five urea plants in Pupuk Kaltim which can be optimized to achieve a maximum profit by utilization of the urea solution distribution. A superstructure optimization model has been developed to determine the optimal urea solution distribution path for production of urea prill and urea granule that gives a maximum net profit. Optimization results show the optimized path of utilization of urea solution when the selling price of urea prill is higher than urea granule is achieved by sending the urea solution to the urea prill plants to maximize the urea prill production and then the remaining urea solutions are sent to the urea granule plants with a lower operating cost. The findings of the sensitivity analysis reveal that the selling price of urea products (prill/granule) is very sensitive and show significant influence on both optimal distribution path and the objective function value. When the selling price of urea prill is higher than urea granule, the maximum net profit is achieved by sending the available urea solution to urea prill plants to produce urea prill up to the maximum capacity of the plants before maximizing the urea granule production. On the other hand, the urea granule plants will be at its maximum production capacity when the selling price of urea granule is higher than urea prill. However, since all urea prill plants have a lower operating cost compared with the urea granule plants, maximizing the production of urea prill become the most profitable option to increase the profit margin. Furthermore, the cost of urea solution will also affect the distribution of urea solution to certain plants which ultimately result in higher economic benefits. The developed optimization framework in this study is recommended to be practically used in the corporate decision-making process with the goal of optimizing the urea production and maximizing corporate profits.

For future work, it is recommended to extend the modeling framework to perform the analysis of the operating cost of urea production and the cost of urea solution. These parameters are directly related with the utilization of urea solutions in obtaining the optimal distribution path. The improvement in these parameters can further increase the economic benefits while increasing the productivity of the urea plants.

Acknowledgements

The authors would like to thank Department of Process and Energy Management at Pupuk Kaltim Fertilizer Company in Indonesia for their support.

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