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Analysis of Bittern Recovery Facility Using Mixed-Integer Nonlinear Programming: Centralized, Decentralized, and Hybrid Scenarios

Erwin Widodo[1*], Furqon Sandiva Utomo Putra[1], Dody Hartanto[1], Niniet Indah Arvitrida[1], Arseto Yekti Bagastyo[2], IDAA Warmadewanthi[2], Totok Soehartanto[3]

[1]*Industrial and Systems Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, East Java, Indonesia*
[2]*Environmental Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, East Java, Indonesia*
[3]*Instrumentation Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, 60111, East Java, Indonesia*

Abstract. The desalination process to produce salts leaves wastewater with a high concentration of minerals called bittern. Most salt producers dump bittern straight away. Such disposal is dangerous to the ecosystem since bittern may increase the environmental salinity. Furthermore, bittern still has potential as it contains minerals that can be extracted and offers value. Consequently, further bittern treatment is necessary to reduce the environmental impact and create a circular economy. However, some specific requirements are needed in determining how to carry out this recovery process. In that, recovery managers need to know the most suitable type and optimal operation variables. These are essential to meet cost-effectiveness and environmental benefits. This research proposes a mixed-integer nonlinear programming (MINLP) model for analyzing the supply and demand of the bittern recovery. This study offers a model to optimize the trade-off between cost and benefits of the recovery process. There are three scenarios to determine the best bittern recovery practices: centralized, decentralized, and hybrid scenarios. The proposed models are then tested and analyzed for their sensitivity due to essential parameters. The numerical analysis has shown that a centralized scenario is best suited for a region with a low bittern supply. Moreover, a hybrid scenario is best suited in an area with a higher bittern supply. In addition, a decentralized scenario is the most suitable option for a region where the number of salt farms is high, and the location is far from the recovery facility.

Keywords: Bittern recovery; Circular economy; Mixed-integer nonlinear programming

1. Introduction

Let us take a prominent example in a country with vast salt consumption, Indonesia. Data have shown that Indonesia produced 2,349,629 metric tons of salt in 2018 (Ministry of Maritime Affairs and Fisheries, 2019). In this country, salts are produced through multilevel processing. The evaporation process of seawater is carried out in the evaporator area. The crystallization process is undertaken in a specific area (PT Garam, 2018). The process resulted in crystallized salt and left wastewater with a high concentration of salt, magnesium, and other mineral called bittern. For every ton of sea salt produced, roughly 1 m3 of bittern is produced (Abdel-Aal, Zohdy, and Abdelkreem, 2017).

[*]Corresponding author's email: erwin@ie.its.ac.id, Tel.: +62-5939361; Fax: +62-31-5939362
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Commonly, bitterns are considered waste and never used again. This waste is problematic because although bittern water contains similar compounds to seawater, it is much more concentrated. When bittern is directly dumped into the ecosystem, the increase in salinity may harm the life in the area (Tewari, 2003). Furthermore, treating bittern solely as an unused by-product of salt production is also a waste of potential since it still contains minerals that can be extracted and have selling value. For every 10 million tons of salt produced, below is the composition of chemicals found in the bittern:

Table 1 Chemical contained in bittern from 10 million tons of salt produced (Abdel-Aal, Zohdy, and Abdelkreem, 2017)

Chemical compound	Tons
NaCl	1,500,000
$MgCl_2$	1,200,000
$MgSO_4$	700,000
KCl	238,000
Bromine	20,000

Those chemicals can still be utilized in other industries, such as cosmetics, energy drinks, and salt industries, for the second time. This estimation shows the potential that can be exploited by treating bittern. Thus, bittern recovery in the salt industry can reduce the environmental impact of salt production but also create a circular economy, which is a system that focuses on reusing, recycling, and recovering to achieve sustainability (Sauvé, Bernard, and Sloan, 2016). Applying the economic concept would contribute to the environment and yield society-wide benefits (Berawi, 2020). Furthermore, it will also follow the sustainable development concept, a balance of economic growth and ecological regeneration (Berawi, 2019).

However, this requires a complex process to maximize the efficiency and effectiveness of the bittern recovery. One needs to know the optimal type and number of recovery stations, considering the bittern supply chain availability and the demand for the extracted mineral. It also needs to be cost-efficient and yield a beneficial result. An approach that can meet this objective is mixed-integer nonlinear programming (MINLP).

MINLP is mathematical programming that has continuous and discrete variables and nonlinearities within its objective function and constraints (Bussieck and Pruessner, 2003). It has a wide range of use, including in the process industry, chemical engineering, and manufacturing. We used this model in a bittern recovery system because some values of variables, such as the number of recovery facilities, need to be an integer, while others (such as cost) do not. Furthermore, as the research objective maximizes circular economy, the function has a non-convex element related to diminishing returns and economies of scale, hence the need to include nonlinearity in the programming.

In achieving a circular economy in wastewater treatment, previous research has studied a circular economy and cleaner production model. This research optimized product-machine allocation using MILP (Rajput and Singh, 2020). Another research on wastewater treatment management that considers both the economy and environment also implemented the MILP approach (Henriques *et al.*, 2020; Zhou et al., 2020; Durkin, Millan-Agorio, and Guo, 2020). In terms of using the MINLP approach, a previous study has proposed a framework that considers the cost and benefit of wastewater treatment (Padrón-Páez, Almaraz, and Román-Martínez, 2020).

In the field of wastewater treatment, several breakthroughs have been proposed. Cotton and carbon material filter was implemented since they offer high sorption capacities and simple preparation processes (Politaeva *et al.*, 2020). In addition, an anaerobic fixed bed reactor (AFBR) was proposed to reduce the odor due to the high protein content in industrial wastewater (Purnomo, Mawaddah, and Bayonita, 2021). Furthermore, Biofloc Technology and Effective Microorganism S4 (EM4) have been attempted to be successful in reducing ammonia and nitrate concentration in the shrimp agro-industry (Suwartha and Pujiastuti, 2017). Moreover, nanofiltration technology was also observed and successfully proven to remove remazol red dye, indigosol brown dye, and sodium sulfide (Na_2S) in the batik textile industry (Istirokhatun *et al*., 2021).

The present study aims to implement the MINLP model for achieving a circular economy, specifically the bittern recovery process. Furthermore, this research extends the scope by comparing possible bittern recovery scenarios between centralized, decentralized, or hybrid types of recovery stations to see which scenario would be the best to apply to certain conditions. The other kind of recovery scenario needs to be weighed in as it affects effectiveness and cost-efficiency. Both profit maximization and the recovery process's environmental impact are considered.

This research considered some factors from the bittern's supply, demand structure, and recovery process constraints. The model is used to maximize the profit by optimizing the trade-off between the cost of waste transportation, recovery, and station investment, benefiting from the selling value of the recovered minerals and the environmental sustainability.

2. Methods

2.1. Conceptual Model

The system discussed is a combination of the supply, demand, and bittern recovery facility. The supplier of bittern, in this case, came from 3 types of salt industries: state-owned industry, privately owned industry, and salt farmers. This differentiation creates the assumption that each industry type has a different amount of output and amount of entity. In that, state-owned and private-owned industries will have larger salt output but fewer entities than salt farmers. The consumer who demands the chemical gained from the bittern recovery process comes from the cosmetic, isotonic, and salt industries, and each requires a different chemical extracted. The bittern recovery facility scenario that would be considered in this research is as follows:

a. Centralized: only one large-scale bittern recovery station
b. Decentralized: several bitter recovery stations are working in parallel
c. Hybrid: the simultaneous combination of both scenarios, working either in series or parallel

A centralized system has a single location that handles the bulk of the demand for bittern recovery. While decentralized means the organization will have multiple treatment hubs as close as possible to the source of bittern, working simultaneously to cover a broader range (Libralato, Volpi, and Avezzù, 2012).

The relationship of the sub-system can be visualized as follow:

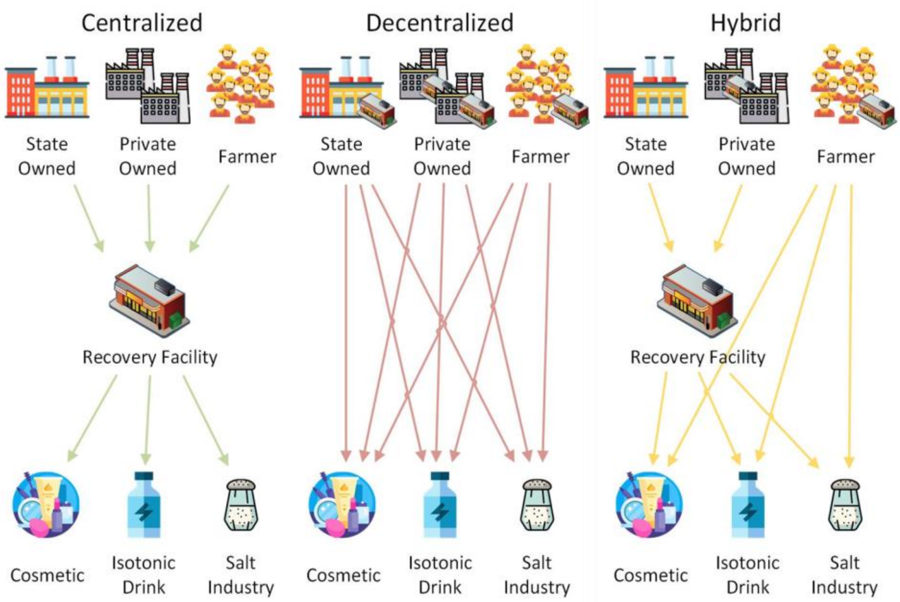

Figure 1 The supply chain flow between the salt industry, bittern recovery facility, and consumers in different scenarios

The above sub-system, later on, will be expressed in cost and benefits variables. The cost variables are facility investment, the bittern recovery process, material handling, and transportation costs. At the same time, the benefit variables came from the revenue from selling the extracted chemical to the consumers and the economic valuation of the environmental benefit from recovering the bittern. The model is also subjected to the amount of bittern supplied, the chemical demanded, and the facility's capacity.

2.2. Mathematical Model

The model is based on MINLP, mathematical modeling involving discrete variables and nonlinear constraint functions (Leyffer *et al.*, 2009). For each scenario described, a model is developed as follows:

2.2.1. Centralized Scenario

Objective function:

Max profit (Z) = recovery revenue + environmental benefit – investment cost – inbound transportation cost – inbound material handling cost - outbound transportation cost – outbound material handling cost – recovery cost

$$\text{MAX}\left\{\sum_{j=1}^{n}\sum_{k=1}^{p}R_{jk}+\sum_{j=1}^{n}E_j-\sum_{j=1}^{n}C_j^{Inv}F_j-\sum_{i=1}^{m}\sum_{j=1}^{n}C_{ij}^{t}V_{ij}-\sum_{i=1}^{m}\sum_{j=1}^{n}C_{ij}^{imh}-\sum_{j=1}^{n}\sum_{k=1}^{p}C_{jk}^{t}B_{jk}-\sum_{j=1}^{n}\sum_{k=1}^{p}C_{ij}^{omh}-\sum_{j=1}^{n}\sum_{k=1}^{p}C_j^{p}B_{jk}\right\} \quad (1)$$

Where R_{jk} is the revenue from selling recovered bittern from facility *j* to consumer *k*; E_j is the economic valuation of environmental benefit gained from the bittern recovery process in facility *j*; F_j is the bittern processing facility, V_{ij} is the mass of bittern supplied from a salt producer *i* to facility *j; B_{jk}* is the mass of recovered chemical sent from facility j to customer *k, C_j^{Inv}* is the yearly investment cost of facility *j*; C_{ij}^{t} is the yearly inbound transportation cost from industry *i* to facility *j; C_{ij}^{imh}* is the yearly inbound material handling cost from industry *i* to facility *j; C_{jk}^{t}* is the yearly outbound transportation cost from facility *j* to consumer *k;* and C_j^{p} is the bittern recovery cost in facility *j.*

The mathematical model (1) is further detailed as follows

Profit (Z)

= recovery revenue + environmental benefit – investment cost – inbound transportation cost – outbound transportation cost – recovery cost

$$\text{MAX}\left\{\sum_{j=1}^{n}\sum_{k=1}^{p} R_{jk} + \sum_{j=1}^{n} E_j - \sum_{j=1}^{n} C_j^{Inv} F_j - \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}^{t} V_{ij} - \sum_{j=1}^{n}\sum_{k=1}^{p} C_{jk}^{t} B_{jk} - \sum_{j=1}^{n}\sum_{k=1}^{p} C_j^{p} B_{jk}\right\} \quad (2)$$

Revenue

= selling price of the chemical × mass of recovered chemical

$$R_{jk} = P_{jk}^{chem} B_{jk} \quad (3)$$

Price of chemical = (maximum demand – actual demand) / chemical price constant

$$P_{jk}^{chem} = \frac{\left(D_{jk}^{max} - D_k\right)}{\beta} \quad (4)$$

Environmental Benefit

= mass of bittern × economic valuation constant of recovering bittern

$$E_j = V_{ij} E_{con} \quad (5)$$

Inbound transportation cost

= distance between industry and facility × transportation cost constant

$$C_{ij}^{t} = S_{ij} C_{con}^{t} \quad (6)$$

Inbound material handling cost

= Material handling cost constant × mass of bittern / maximum material handling capacity

$$C_{ij}^{imh} = \frac{C_{con}^{mh} V_{ij}}{F^{mh}} \quad (7)$$

Outbound transportation cost

= distance between facility and consumer × transportation cost constant

$$C_{jk}^{t} = S_{jk} C_{con}^{t} \quad (8)$$

Outbound material handling cost

= Material handling cost constant × mass of recovered chemical / maximum material handling capacity

$$C_{jk}^{omh} = \frac{C_{con}^{mh} V_{ij}}{F^{mh}} \quad (9)$$

Where C_{ij}^{omh} is the yearly outbound material handling cost from industry *i* to facility *j*; P_{jk}^{chem} is the price of the chemical compound sent to consumer *k* from facility *j*; D_{jk}^{max} is the maximum demand of chemical compound sent to consumer *k* from facility *j*; D_k is the actual demand of chemical compounds from consumer *k*; S_{ij} is the distance between salt producer *i* to facility ; S_{jk} is the distance between facility *j* to consumer *k; β* is the price constant of chemical compound (Rp/mass); E_{con} is the economic valuation constant of environmental benefit from recovering bittern (mass/R) ; C_{con}^{t} is the transportation cost constant (Rp/distance/mass); C_{con}^{mh} is the material handling cost constant (Rp/mass); F^{mh} is the single-trip material handling capacity.

Constraint:

1. Neither input nor output mass can exceed the facility's capacity.

$$\sum_{j=1}^{n} V_{ij} \leq \sum_{j=1}^{n} F_j^{cap} \quad (10)$$

$$\sum_{j=1}^{n} B_{jk} \leq \sum_{j=1}^{n} F_j^{cap} \quad (11)$$

2. The mass of chemical output extracted from the bittern is less than the bittern mass itself.

$$\sum_{j=1}^{n} V_{ij} \geq \sum_{j=1}^{n} B_{jk} \tag{12}$$

3. Demand is assumed to be equal to the mass of chemicals supplied due to implementing a pull system.

$$D_k = B_{jk} \tag{13}$$

4. The system will only fulfill a profitable demand.

$$\sum_{j=1}^{n}\sum_{k=1}^{p} R_{jk} \geq \sum_{j=1}^{n} C_j^{Inv} F_j + \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}^{t} V_{ij} + \sum_{j=1}^{n}\sum_{k=1}^{p} C_{jk}^{t} B_{jk} + \sum_{j=1}^{n}\sum_{k=1}^{p} C_j^{p} B_{jk} \tag{14}$$

5. Non-negative variables

$$R_{jk}, V_{ij}, B_{jk}, C_j^{Inv}, C_{ij}^{t}, C_{jk}^{t}, C_j^{p}, P_{jk}^{chem}, D_{jk}^{max}, D_k, S_{ij}, S_{jk}, F_j^{cap} \geq 0 \tag{15}$$

6. Only one facility is built.

$$F_j = 1 \tag{16}$$

$$n = 1 \tag{17}$$

Where F_j^{cap} is the capacity of facility j,

2.2.2. Decentralized Scenario

Objective function:

Max profit (Z) = recovery revenue + environmental benefit – investment cost –outbound transportation cost – outbound material handling cost – recovery cost

$$\text{MAX}\left\{\sum_{j=1}^{n}\sum_{k=1}^{p} R_{jk} + \sum_{j=1}^{n} E_j - \sum_{j=1}^{n} C_j^{Inv} F_j - \sum_{j=1}^{n}\sum_{k=1}^{p} C_{jk}^{t} B_{jk} - \sum_{j=1}^{n}\sum_{k=1}^{p} C_{ij}^{omh} - \sum_{j=1}^{n}\sum_{k=1}^{p} C_j^{p} B_{jk}\right\} \tag{18}$$

As each salt producer has its bittern recovery facility, inbound transportation cost and material handling are assumed to be zero. Constraints (10) to (16) were then applied.

2.2.3. Hybrid Scenario

Objective function:

Max profit (Z) = Max profit Centralized + Max profit decentralized

A new index (l) is introduced to differentiate the centralized and decentralized equation to solve this. The centralized max profit is as follows:

Max profit centralized = centralized recovery revenue + environmental benefit – investment cost – inbound transportation cost from a salt producer i to facility j – inbound material handling cost – outbound transportation cost from facility j to consumer k – outbound material handling cost – recovery cost

$$\text{MAX}\left\{\sum_{j=1}^{n}\sum_{k=1}^{p} R_{jk} + \sum_{j=1}^{n} E_j - \sum_{j=1}^{n} C_j^{Inv} F_j - \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}^{t} V_{ij} - \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}^{imh} - \sum_{j=1}^{n}\sum_{k=1}^{p} C_{jk}^{t} B_{jk} - \sum_{j=1}^{n}\sum_{k=1}^{p} C_{ij}^{omh} - \sum_{j=1}^{n}\sum_{k=1}^{p} C_j^{p} B_{jk}\right\} \tag{19}$$

While the decentralized max profit is as follows:

Max profit decentralized = decentralized recovery revenue + environmental benefit – investment cost - outbound transportation cost from salt producer l to consumer k – outbound material handling cost – recovery cost

$$\text{MAX}\left\{\sum_{l=1}^{n}\sum_{k=1}^{p} R_{lk} + \sum_{j=1}^{n} E_l - \sum_{l=1}^{n} C_l^{Inv} F_l - \sum_{l=1}^{q}\sum_{k=1}^{p} C_{lk}^{t} B_{lk} - \sum_{j=1}^{n}\sum_{k=1}^{p} C_{ij}^{omh} - \sum_{j=1}^{n}\sum_{k=1}^{p} C_j^{p} B_{lk}\right\} \tag{20}$$

Each equation follows constraints (10) to (16) and is summed up together.

The mathematical models are then run into LINGO, a tool to build and solve linear, nonlinear, quadratic, stochastic, and integer optimization programming (LINDO, n.d.). The data of environmental benefits is approximated from the literature review, while transportation cost and material handling costs are approximated using the local gas price and labor cost.

3. Results and Discussion

3.1. Model Running Results

Below are the results of the model running test:

Table 1 Model running results (in a million rupiah)

	Centralized	Decentralized	Hybrid
Total Revenue	563,169.6	606,015.7	395,461.6
Environmental Benefit	117,659.3	114,279.2	43,136.38
Investment Cost	1,000	500	1,350
Inbound transportation cost	58.226340	-	56,895
Inbound material handling	85,315.53	-	11,671.07
Outbound transportation cost	117,355.4	201,851.3	111,487.65
Outbound material handling	14,444.12	14,444.12	9,388.676
Recovery cost	61,880	309,400	114,478

Our calculation assumes that the environmental benefit was gained through economic valuation by performing wastewater treatment (Hernández-Sancho, Molinos-Senante, and Sala-Garrido, 2010). Our numerical experiment shows that the centralized scenario yields the highest profit at the value of Rp 400,833.9 million, followed by the decentralized with Rp 193,599.5 million and the hybrid scenario with Rp190,222.5 million. When we compare the revenues under centralized and decentralized scenarios, the latter is slightly higher than the former. Nonetheless, the decentralized scenario yields lower overall profit than that under centralized. The reason is the total processing cost of a decentralized scenario is way higher than the centralized one. Another reason is centralized scenario experience benefits from an economic scale. This situation makes its corresponding investment considerably cheaper (Mourtzis and Doukas, 2012). When we proceed to the following comparison between decentralized and hybrid scenarios, the former yields higher profit than the latter. This is due to higher facility investment costs under the hybrid scenario. In addition, both scenarios still incur considerably high inbound transportation and material handling costs.

To compare our results to those with similar works of centralized versus decentralized and hybrid concepts for water waste treatment, we reviewed some related articles. By using specially constructed wetlands in China, decentralized and sometimes hybrid wastewater systems may overcome the efficiency of the centralized system (Ying et al., 2021). This fact is contrary to our initial numerical experiment results. In addition, a study of non-targeted analysis with gas chromatography-spectrometry was conducted to evaluate the performance of centralized versus decentralized water waste systems in the USA and South Africa (Mladenov *et al.*, 2022). Surprisingly, the decentralized system was found to perform better than the centralized one.

Moreover, a study to assess the efficiency of rural sewage treatment (RuST) was conducted by using centralized and decentralized scenarios (Yuansheng *et al.*, 2021). An interesting result was revealed when it was found that the centralized scenario does not always provide the best result. By proposing rural residents' spatial pattern (RESP) and the optimal pattern of RuST, a decentralized scenario offers a better outcome for water waste treatment.

We decided to proceed with our numerical experiment further based on those aforementioned exciting facts. As the primary purpose of this research is to create a model that can be used in decision-making, it is not enough to have a single result, as shown in

Table 1. Thus, sensitivity analysis is applied to two important parameters in our proposed model: annual bittern supplied and the proportion of salt produced by each industry type.

3.2. Profit sensitivity on annual bittern supply

In the first sensitivity analysis, the author changes the value of the annual bittern supplied.

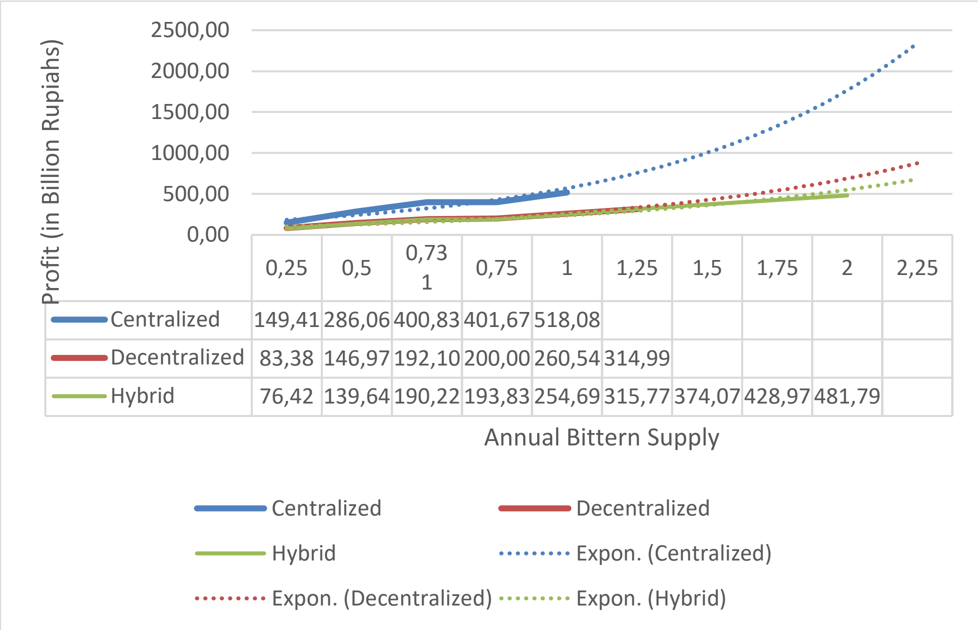

Figure 2 Profit sensitivity on the changes in annual bittern supply

Predictably, the total profit would exponentially increase with more supply of bittern. However, each scenario would eventually reach its infeasible point, meaning it can no longer fulfill the constraints due to the cost incurred becoming too high. The centralized scenario is the first to do so. The reason is that with the highest material handling and transportation cost that linearly increases with the rise of bittern supply, it reaches a point where it is no longer economically feasible. This situation happens when the bittern supply reaches 1.25 million tons per year.

Moreover, the decentralized scenario became infeasible when the bittern supply reached 1.5 million tons per year. The reason is the processing cost became too overwhelming, and the revenue could not keep up. The outbound transportation cost also became too expensive as it needed to transport the resulting chemicals to each buyer from each of the respective salt farms. Additionally, while applying the decentralized scenario to the 1.25 million tons supply mark is still feasible, the hybrid scenario has become more profitable. The reason is that it has a much lower recovery cost than the decentralized scenario. The scenario would remain feasible until the bittern supply reaches 2 million tons annually.

Thus, if the decision-maker intends to utilize the full extent of bittern available in their region, it is more recommended to use the hybrid scenario to accommodate a larger volume.

3.3. Profit sensitivity on the proportion of salt produced from industry type

In the second sensitivity analysis, the author changed the proportion of salt annually produced by each industry type. The results would show how the ideal scenario would vary depending on which kind of industry is contributing the most towards the salt and bittern supply. In this case, the centralized scenario is not considered, regardless of the proportion.

Each industry type would send its bittern to a single facility. However, changing the proportion of salt produced in decentralized and hybrid cases would affect the amount of bittern being processed in each facility. For instance, if a salt farmer produces only 20% of salt in a hybrid scenario, the centralized facility needs to handle 80% of the salt produced. And so on and so forth.

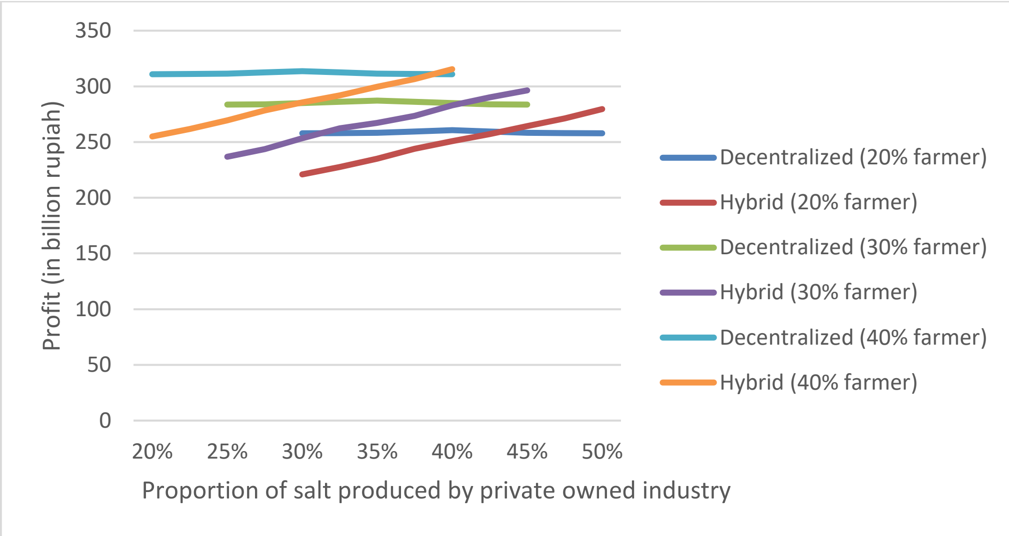

Figure 3 Profit sensitivity on the changes in the proportion of salt produced in each industry type

The analysis shows that both decentralized and hybrid scenarios would increase profit as salt farmers' proportion of salt increases. The reason is that inbound transportation and material handling costs will reduce if more bitterns are processed in-house. Increasing the bittern percentage supplied by salt farmers would eventually make the decentralized scenario more profitable than the centralized one.

However, when looking at how the proportion of state-owned and private-owned industries is divided, it shows different tendencies. While the hybrid scenario would exponentially increase profit, the decentralized scenario would be flatter. Although not by a large margin. The reason is that private-owned and state-owned industries have fewer plan quantities than salt farmers, benefiting from the economy of scale of a centralized recovery facility than a decentralized one. This decentralized scenario would eventually be less profitable than a hybrid scenario when the salt farm proportion is not overwhelmingly dominating compared to the other two industry types.

As an interesting note, even though it is considered a "salt farmer" in this research, the same principle is also applied in the condition where the salt farms in a region are a lot and far in between, regardless of the owner of said factory. Thus, a decentralized scenario would be preferable if a decision-maker wants to apply a bittern recovery scenario in a region where that situation is prominent.

4. Conclusions

The research has proposed three different scenarios of the bittern recovery process. Each scenario could be profitable when applied to certain conditions. Our numerical experiment has successfully shown some model behavior as evidence on which scenario is more financially preferable to use. However, the implementation of such scenarios would depend on several different circumstances. Our proposed model set works based on profit optimization. Such mathematical representation can provide some optima in a numerical result of decision variables that maximizes circular economy benefit. This process is done by maximizing the revenue items consisting of the cost of extracted chemicals and environmental benefits and minimizing the associated cost, including transportation, material handling, investment, and recovery cost. Some insights derived from our analysis can assist decision-makers of bittern recovery processes in selecting which bittern recovery scenario is the best-suited option. The centralized scenario is best suited when in a region with a low bittern supply. The hybrid scenario is best suited in a region with a higher bittern supply. The decentralized scenario is best for a region where the salt farms are a lot and far in between. Nonetheless, there are some limitations and drawbacks to this research. Hence, some betterment is interesting as future works are done by transforming the model into a dynamic model instead of a deterministic one, allowing for more accurate results. Future works can also expand the model for other scenarios.

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