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A simple tool for resource availability optimization: A case study of dairy whey supply for single cell protein and oil production in Latvia

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Abstract. Single cell proteins (SCP) and oils (SCO) are promising alternatives for replacing conventional feed ingredients in animal and aquaculture fish feeds. The production costs of SCP and SCO need to be reduced by using inexpensive substrates (production by-products) suitable for cultivation of protein and oil producing microorganisms. This article reviews the availability of milk processing by-product – whey in Latvia, in 2019. Additionally, a simple production plant location optimization model is proposed, where no prior knowledge of location optimization or experience with dedicated software is required from the user. The case study demonstrated that the model is valid, and it can be used as a simple tool for resource acquisition from multiple sources to single production plant.

Key words: availability analysis, biomass supply chain, dairy waste, location optimization, whey.

INTRODUCTION

Single cell protein (SCP) and single cell oil (SCO) are recognized as one of the most promising alternatives for replacing animal feeds, in particular aquaculture fish feeds (Spalvins & Blumberga, 2018). However, current production costs of SCP and SCO hinder the wider use of these products in feed production (Spalvins & Blumberga, 2018). In order to make SCP and SCO production costs more economically viable, it is necessary to use cheap substrates for microbiological fermentations (Spalvins & Blumberga, 2018).

In order to evaluate the substrates for the production of SCP and SCO, it is necessary to perform data analysis and determine the total substrate volumes available in specific regions or globally as a whole. In addition, it is necessary to identify the current use for specific substrates and compare whether the current use has higher added value than the production of SCP and SCO. However, such a superficial analysis is not sufficient to determine whether the use of a particular substrate will indeed be economically justified. Additional in-depth availability analysis is needed to calculate procurement costs, local availability, required transportation and logistics systems.

Spalvins & Blumberga (2018) previously reviewed the most appropriate tools for substrate availability analysis at three different levels: biomass supply chain between producer and processing plant; biomass supply chain between multiple producers, biomass logistics system (biomass transporters) and single processing plant; supply chain of multiple applicable biomass types on national level for multiple processing plants. Biomass supply chain between producer and processing plant was based on the integrated biomass supply analysis and logistics model devised by Sokhansanj et al. (2006). Biomass supply chain between multiple producers, biomass logistics system (biomass transporters) and single processing plant was based on simulation and optimization model devised by Ebadian et al. (2013). Supply chain of multiple applicable biomass types on national level for multiple processing plants was based on biomass availability assessment model devised by Welfle et al. (2014). In this study simplified model of biomass supply chain between multiple producers, biomass logistics system (biomass transporters) and single processing plant was developed and utilized. A more detailed description of the availability models for each level is described in detail by Spalvins & Blumberga (2018), Sokhansanj et al. (2006), Ebadian et al. (2013) and Welfle et al. (2014).

Spalvins et al. have reviewed most of the cheap agricultural and industrial by-products applicable for SCP and SCO production (Spalvins et al., 2018a; Spalvins et al., 2018b; Spalvins & Blumberga, 2019; Spalvins et al., 2019), but information on the availability and potential price of each specific by-product, if used in fermentation, is very limited. Consequently, this publication analyses the availability of one of the potential substrates - dairy residues. Whey and other dairy processing by-products are characterized by high levels of chemical oxygen demand (~75 g kg^{-1}) and biological oxygen demand (54 g kg^{-1}), due to high concentrations of lactose (~4.7%) (Slavov, 2017), lipids and other organic compounds (Brião, & Granhen Tavares, 2007). In EU due to high COD and BOD levels whey cannot be released in local water bodies or even in local wastewater treatment systems without prior pre-treatment (Valorlact, 2012). Therefore, dairy industry is required to lower the COD and BOD levels before whey can be released in local wastewater systems, which in turn creates additional costs for dairy processing plants. Many companies are looking for solution to process whey generated from cheese and cottage cheese production. The solutions used in Latvia are the processing of whey into whey powder, whey protein powder, lactose powder, whey drinks etc., however, this solution involves high upfront investments and the use of spray drying is characterized by high energy consumption and relatively low efficiency (Cheng et al., 2018). Some companies in Latvia partner with local biogas plants to use generated whey as feedstock for anaerobic fermentations. Although, this is only possible if the biogas plant is nearby and biogas production in general is a solution with significantly lower added value than utilization of the same feedstocks in SCP or SCO production (Spalvins et al., 2018a).

To calculate the substrate availability and to find optimal location for the SCP or SCO plant, a simple and quick-to-use model was developed, which is based on the calculation and validation of the initial site location and validation to confirm the accuracy of the results.

MATERIALS AND METHODS

Data collection

Initially, all available information on the amount of whey generated in Latvia was collected. This was done mainly by summarizing the available information on the cheese production volumes of each milk processing company in Latvia. It was then assumed that approximately 9 and 0.6 litres were generated per kilogram of cheese and cottage cheese respectively.

Although in Latvia, according to NACE (Statistical classification of economic activities in the European Communities) rev. 2 classification, 61 companies correspond with 10.51 class (Operation of dairies and cheese making) (Lursoft, 2020), after interviewing the representatives from Central Statistical Bureau of Latvia (CSB), they informed us that statistics on cheese production are collected only from 22 companies. These companies are centralized medium to large capacity dairy plants, which produce the vast majority of aged and fresh cheese in the country. The rest are either not specialized in the production of cheese, but fall under NACE class 10.51 or are small domestic producers, farms or sole traders who have very small production capacities and whose products are sold mainly in local markets. Therefore, the exclusion of these remaining companies from the statistics in this study does not have pronounced effect on the accuracy of the simulation, because the whey collection in small volumes is not cost-effective and would have not be done in real life scenario as well. The sources of information were data of the Central Statistical Bureau of Latvia (CSB) (CSB, 2020), information on individual companies available in mass media and companies' websites, as well as interviews of dairy processing plant representatives. CSB provided the most detailed information on the monthly production volumes of aged and fresh cheese. Due to Latvian Statistics Law (OP number: 2015/118.3) which is prepared following the guidelines of the European Statistics Code of Practice, the data provided by CSB could not contain information that would allow to directly identify specific companies to their respective cheese production volumes. Therefore, the data received from CSB was arranged by the territorial entities and not the companies, thus allowing for indirect identification of specific companies and their production volumes, which is in line with Latvian Statistics Law if data is used for research. Apart from research this does not apply for other purposes, therefore in order to follow the limitation put in place by the law, in this publication no specific data on the production volumes will be given.

Optimization model

The initial optimization model was developed using MS Excel, MS Visio and Google Maps. On the map of Latvia, the locations of all milk processing plants (B_n) were marked, also the calculated whey volumes (W_ns un W_nsu) were assigned for each relevant dairy plant. The map of Latvia was placed on XY axis and on each axis value ($A_{i,z}$) the distance (D_n) in a straight line was calculated using Pythagorean theorem (Fig. 1, B; Fig. 3; Eq. 1). Followed by calculation of the given company's (n) coefficient ($K_n^{A_{i,z}}$) for the given coordinates of the particular potential SCP/SCO plant (i, z) (Fig. 1, C; Fig. 3; Eq. 2). $K_n^{A_{i,z}}$ value is calculated for every company, for every possible coordinates of the potential SCP/SCO plant.

Formulas for the initial optimization model:

$$D_n = \sqrt{(A_i x - B_n x)^2 + (A_z y - B_n y)^2} \quad (1)$$

$$K_n^{A_{i,z}} = D_n \times (W_n s - W_n su) \quad (2)$$

$$P_{i_0 \ldots i_{106}, z_0 \ldots z_{64}} = \sum K_{n_1 \ldots n_{22}}^{A_{i,z}} \quad (3)$$

where $A_{i,z}$ – SCP/SCO plant coordinates ($A_i x$, $A_z y$), i = {0…106}; z = {0…64}; B_n – particular dairy plant (n) coordinates ($B_n x$, $B_n y$), n = {1…22}; $W_n s$ – the quantity of generated whey in a given dairy plant (n), tonnes; $W_n su$ – consumption of whey in processes unrelated to SCP/SCO production in a given dairy plant (n), tonnes; D_n – distance from variable SCP/SCO plant (i,z) to particular dairy plant (n); $K_n^{A_{i,z}}$ – coefficient of the given company (n) for the given coordinates of the particular SCP/SCO plant (i,z); $P_{i,z}$ – SCP/SCO plant location (i,z) potential.

Summing the coefficients of all companies for the given SCO/SCP plant coordinates gives the potential of the each particular location (Fig. 1, D; Fig. 3; Eq. 3): the lowest calculated $P_{i,z}$ value represents the location where the largest amount of whey can be delivered to by traveling the shortest distance.

To validate the optimization model, initially the optimal coordinates (20 lowest $P_{i,z}$ values) were used to mark the area. This area was used to validate the optimization model. Settlements with a population over 100 were evenly marked in the area (n = 24). These settlements were used to recalculate real distances using national and local roads using Google Maps. This was done because the largest rivers of Latvia (Daugava, Gauja, Lielupe) can only be crossed at certain locations, so the real distance for some dairy plants may change significantly and thus the optimal location for the SCP/SCO plant may also change. The resulting distances from each company to each of the settlements in the optimal area were used in the calculations just as in the initial optimization calculation for calculating $K_n^{A_{i,z}}$ value, only this time it was done by replacing D_n value with real distances travelled via motorways.

Example for locating the lowest validated $P_{i,z}$ value (Fig. 1):

- Gather information on generated/available by-product in area of interest;
- Put the area of interest on XY axis using MS Visio, every coordinate on the XY axis is the potential SCP/SCO plant coordinates ($A_{i,z}$) (Fig. 1, A);
- Locate the main production plants (B_n) that generate the by-product ($W_n s$ – $W_n su$) (Fig. 1, A);
- Calculate the distance from production plant location to every XY coordinates (D_n) by using Pythagorean theorem (MS Excel) (Fig. 1, B);
- Calculate the initial $P_{i,z}$ values by multiplying distance values with amount of by-product generated and then summing all the $K_n^{A_{i,z}}$ values for the given SCP/SCO plant location (Fig. 1, C);
- Lowest $P_{i,z}$ value is the initial optimal SCP/SCO plant location (Fig. 1, D, grey square);
- Any number (in this case n = 6) of lowest initial $P_{i,z}$ values can be used to draw the initial optimal area from which populated locations will be Fig. 1, E, F).

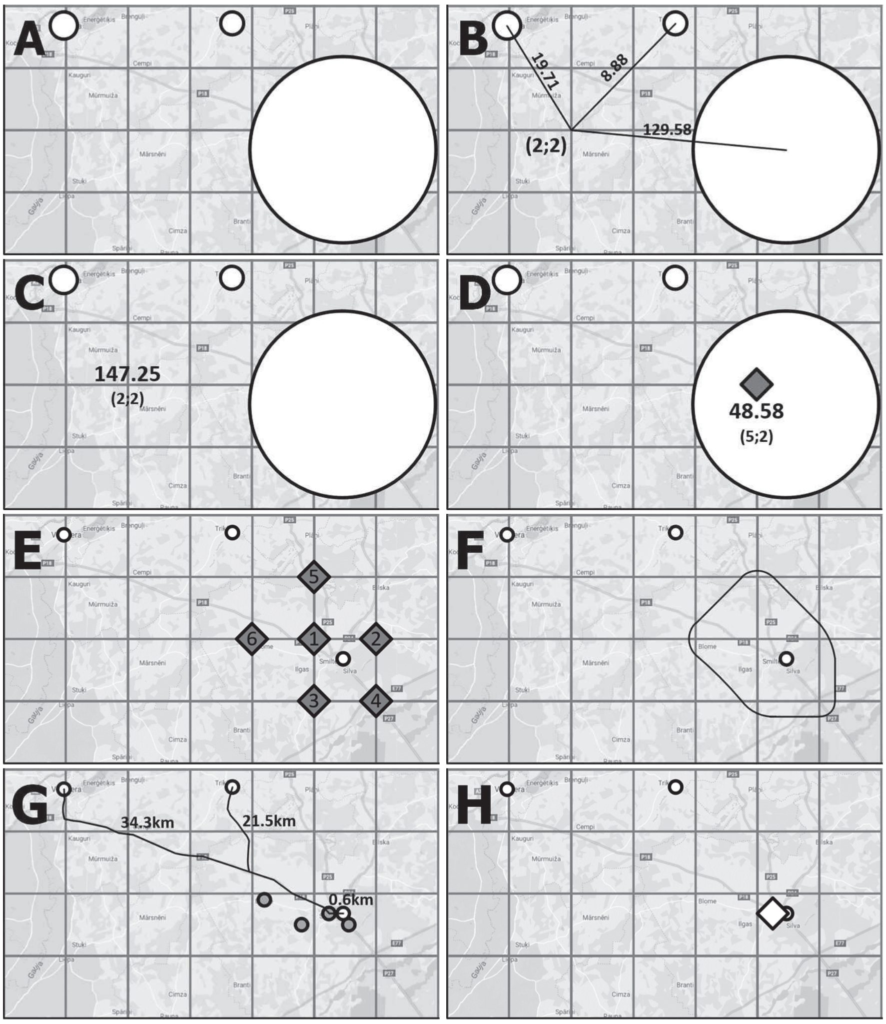

Figure 1. Visual example for locating and validating the optimal location for by-product processing plant with lowest validated $P_{i,z}$ value (white square). A – area of interest on XY axis, with by-product-generating plants (white circles proportional to generated substrate volumes); B – distance measurement using Pythagorean theorem from by-product generator to (2;2) coordinates in the area; C – calculated $P_{i,z}$ value for single coordinates; D – coordinates with the lowest $P_{i,z}$ value marked in the map (gray square); E – six lowest $P_{i,z}$ value marked in the map (gray squares); F – six lowest $P_{i,z}$ values used to mark initial optimal area from which populated locations will be selected; G – by using Google Maps distance via motorways is calculated for every populated location within initial optimal area (gray circles); H – populated location with the lowest $P_{i,z}$ value (white square) is the validated optimal location for the by-product processing plant.

- Distance from selected populated locations can be measured using Google Maps to every production plant (Fig. 1, G);
- If the maps lower left corner is aligned with XY (0:0) coordinates, the aligned locations for the production plant can be easily found in the shape coordinates in MS Visio;

- Settlements within the initial optimal area (Fig. 1, F) can be validated by recalculating the distance via motorways, thus obtaining the validated optimal SCP/SCO plant location (Fig. 1,G, white square);
- Calculation is finished by locating the populated location with the lowest $P_{i.z}$ value (see Fig. 1, H, white square). To this populated location the largest amount of by-product can be delivered while driving the shortest total distance.

RESULTS AND DISCUSSION

Data collection

The aggregated data on the amount of whey generated by Latvian dairy plants are shown in Fig. 2. From this data it can be concluded that the cheese production volumes in Latvian dairy plants are distributed evenly over Latgale and Vidzeme districts. In Kurzeme and partially in Zemgale districts situation is different due to large volumes of fresh milk that is being exported to neighbouring country Lithuania. This also outlines a problem within dairy industry of Latvia, where approximately 2,000 tonnes of fresh milk are produced every day, while only 1,300 tonnes are processed in local dairy plants (LSM, 2014). The other 700 tonnes are processed in neighbouring countries and then portion of it is sold back in Latvia. This way Latvian dairy industry and Latvian economy as a whole is losing vast amounts of potential revenue due to export of low added value raw material (fresh milk) and import of value added products (dairy products) while essentially the origin of both products is the same.

Figure 2. The aggregated data on the amount of whey generated by Latvian dairy plants. Circle sizes are proportional to the amount of whey generated in the specific dairy plant (n = 22).

Problem with the calculation of the total whey volume was that the amount of whey generated per kilogram of finished product differs significantly between aged and fresh cheese. Thanks to data provided by CSB it was possible to accurately calculate the volumes of generated whey from both types cheese. It is also important to distinguish aged and fresh cheese whey from one another not only because of the different amounts generated per kilogram of product, but also because fresh cheese whey has lower pH (6–7 pH and 4.5–4.8 pH for aged and fresh cheese whey respectively) which can significantly affect the SCP and SCO yields. In Latvia a total of 30961 tonnes of aged cheese and 19,977 tonnes of fresh cheese where produced in 2019. Which generated approximately 278651 tonnes of aged cheese whey and 11,986 tonnes of fresh cheese whey. Aged cheese whey constituted a majority of whey – 95.88%, while fresh cheese whey only constituted 4.12%. Therefore, a whey-utilizing SCP/SCO production technology should give the main focus on improving efficiency of utilizing solely whey from aged cheese.

During data collection it was also concluded that most dairy plants in Latvia are highly specialized for production of certain dairy products. Some almost exclusively produce aged cheese (Preilu siers, AS), some specialize in sweet cottage cheese bars (Rigas piena kombinats, AS), while others mainly produce various types of yogurts (Tukuma piens, AS) etc.

Optimization model

The initial optimization model was used to find the optimal area (Fig. 3) and to mark a point in map with the lowest $P_{i,z}$ value (Fig. 3, grey square). By validating the optimization model and replacing the distance of straight lines with real distances via motorways, it was found that the lowest P value deviated by only 7.96 km (Fig. 3., black square) from the initial point with lowest $P_{i,z}$ value and the validated optimal location was still within the initially marked area. This indicates that the initial optimization model has, with very little deviation, indicated the optimal SCP/SCO plant location, which also confirms that this model can be used to find optimal production plant location.

Figure 3. Coordinates of the optimal location of the production plant, depending on the amount of whey generated in dairy processing companies in Latvia. Initial optimal area (white area) was located by marking 20 coordinates with the lowest $P_{i,z}$ values. Grey square – lowest initial $P_{i,z}$ value. Lowest validated $P_{i,z}$ value (black square) was located by recalculating distances from dairy plants to potential production plant sites inside initial optimal area via motorways. Model XY axis resolution: i = {0…106}; z = {0…64}.

In this case study the 20 lowest initial $P_{i,z}$ values were used to draw initial optimal area (Fig. 3), but since number of selected initial $P_{i,z}$ values is arbitrary selected it can be changed depending on particular case study and users preferences. If larger number of initial lowest $P_{i,z}$ values are used the number of selected populated areas will also be larger which in turn will make the validation process more time consuming, therefore balance with selected XY axis resolution (in this case i = {0…106}; z = {0…64}) and size of the initial optimal area need to be considered to keep the calculations manageable. In the case study a single step on XY axis was about 4.2 km, which might have been too high resolution since similar results could be obtained, for example, by using half of XY axis resolution (Fig. 4). Although the initial optimal area is less refined due to decreased resolution (i = {0…53}; z = {0…32}; single step on XY axis ~8.4 km; deviation from initial $P_{i,z}$ value to lowest $P_{i,z}$ value after validation was 14.72 km), the lowest validated

$P_{i,z}$ value is still within the initial optimal area, which in this case was created from only 10 lowest initial $P_{i,z}$ values (Fig. 4). This shows that model can be successfully used even with significantly decreased XY resolution. The decreasing of XY resolution by half did not affect the final result of the optimal SCP/SCO plant location while also significantly decreasing the amount of calculations that are required to perform the analysis via MS Excel. With i = {0…106}; z = {0…64} XY resolution, the model required to calculate 6955 $P_{i,z}$ values, while with halved resolution i = {0…53}; z = {0…32}, the model required only 1782 $P_{i,z}$ values to be calculated thus decreasing the amount of required calculations almost 4 fold, while still providing with the same results final results. This shows that model can be adjusted for user's preferences while also making the calculations more manageable.

Figure 4. Optimization model repeated with halved XY axis resolution: i = {0…53}; z = {0…32}. Initial optimal area (white area) was located by marking 10 coordinates with the lowest $P_{i,z}$ values. Grey square – lowest initial $P_{i,z}$ value.

CONCLUSIONS

By interviewing two companies for this study, it became apparent that companies lack capacity to provide the researchers with requested data, since data acquisition takes a long time and usually employees are unwilling to spend additional hours for data gathering. Also, the provided information about the dairy plants current use of cheese and cottage cheese whey should be taken with some scepticism, as company representatives are unlikely to disclose if some of the whey is discharged into local wastewater system or in natural water bodies without prior treatment. Both companies stated that they process or treat 100% of the generated whey, although estimates (Valorlact, 2012) state that at least 25% of the generated whey in EU is not disposed of properly or is not reprocessed in new products. Of course, this might also not be the case in Latvia and possibly all of the generated whey is treated properly or reprocessed, but with currently conflicting information it is difficult to know for sure. Complete data for generated aged and fresh cheese volumes was provided by CSB, thus it was possible to perform analysis with accurate data for the generated whey amount in each of the 22 dairy companies.

The current model assumes that all generated whey is used in SCP/SCO production, which is not accurate, because in reality some of the dairy plants use whey for production of other value added products. Such products as whey powder, whey protein powder, lactose powder, whey drinks etc. are also products with higher added value than SCP or SCO. Therefore, further data acquisition is required in the future to calculate the available whey volumes in each dairy plant. This could be done by further interviews for the production volumes of alternative products which use whey as main ingredient or by acquiring data via other sources – CSB, media etc. Since most of the generated whey in Latvia is aged cheese whey (95.88%) the SCP and SCO production should focus on using only this type of whey. By using the reported SCP and SCO yields when using whey as substrate (Paraskevopoulou et al., 2003; Vamvakaki et al., 2010; Yadav et al., 2014), in Latvia, it would be possible to produce up to 800 tonnes of pure SCP (Paraskevopoulou et al., 2003) or up to 2,250 tonnes of pure SCO (Vamvakaki et al., 2010). SCO also has wider possible applications (feeds, biofuel, building block chemicals etc.) (Ratledge, 2013; Spalvins & Blumberga, 2019) and higher market price (Spalvins & Blumberga, 2018), therefore it can be concluded that SCO is the preferable end-product if whey is used as a substrate.

After validation, the developed model confirms that it is possible to calculate the optimal SCP/SCO plant location. Use of model itself is simple, quick and does not require any prior knowledge in using dedicated optimization or dynamic modelling software. This model can be used to optimize the sourcing of any raw material, in any industry where the situation requires the raw material to be gathered from multiple sources and transported to single processing plant. Therefore, the proposed model can be used for modelling the sourcing of by-products not only applicable for SCP or SCO production, but also for other purposes, such as sourcing of starch rich by-products for ethanol fermentations, sourcing of vegetable oil rich by-products and wastes for fuel production (biodiesel), sourcing of lignocellulose rich by-products and waste materials for lignocellulose hydrolysis followed by ethanol production etc.

In the future, the model need to be refined by following improvements:

By taking into account the number and capacity of transporting trucks and optimization of the route from raw material supplier to another, if it is not possible to load the truck fully in single source;

By introducing a dynamic model of the SCP or SCO production process to find the optimal production capacity (bioreactor volumes), while also taking into account the amount of feedstock supplied daily and the very short shelf life of the feedstock (for whey it is 24 hours);

Improve the dynamic model of the transport and production process by introducing a cost estimation that could also demonstrate whey viability for use in SCP and SCO production, by taking into account the market price of the final product;

Ensuring that developed model is easily adjustable for different types of feedstocks applicable for SCP and SCO production.

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