New Concawe linear programming model

Concawe's linear programming model was completely rebuilt in 2022 to provide the capability needed to address the upcoming challenges faced by the European refining system in the context of the low-carbon economy transition. It can now be used to anticipate and simulate the potential evolution of the current refining system and the alternatives for low-carbon liquid fuels production, and is flexible enough to be upgraded more easily and more quickly as needed in the future.

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What is an LP model and why is it used in the refining industry?

Linear programming is a mathematical modelling technique used to maximise or minimise a function of several variables subject to a number of constraints. The functions being optimised and the constraints are linear, meaning that the constraint does not contain a variable squared, cubed or raised to any power other than one, a term divided by a variable, or variables multiplied by each other. Also, proportionality must exist. In other words, for every unit increase or decrease in a variable, the value of the constraint increases or decreases by a fixed amount.

General linear programming deals with the allocation of resources, seeking their optimisation.[1]

The purpose of an oil refinery is to turn crude oil into marketable products in the most efficient and economical way. A particular refinery generally supplies particular markets which set the quality of the products to be supplied and, to an extent, the amount of each grade. Depending on the geographical location of the refinery, there can also be opportunities to export to other markets. The refinery has access to certain crude oils and other feedstocks, the range of which is a function of its location and the way it is supplied (e.g. by ships or pipelines). Finally, the refinery features a given combination of process units (generally referred to as its 'configuration').

Refinery operation is thus characterised by multiple real constraints arising from feedstock supply, product demand (quantity and quality) and process unit limitations. Yet, there are many ways of operating within these constraints and refiners have always strived to optimise their operation in order to maximise profit or minimise costs to supply a given market demand within a given set of product prices and input costs. The tool used to that end by refiners worldwide is known as linear programming which, given a quantity to be optimised, aims at identifying the optimum solution amongst the myriad of possible solutions to a complex problem.

For a given set of desired products, the LP solution tells the refiner how much of each available feedstock should be processed, the level at which each refinery process unit will be utilised and, more generally, which amongst all the constraints will actually be binding. Crucially, it also provides information on the impact on the objective function of a marginal change in each of the binding constraints (the so-called 'marginal values'). This last property of an LP solution was used, for instance, to assess the CO_2 intensities of refining products in a Concawe study undertaken in 2017.[2]

Given the complexity of a refinery model, which in the case of the current Concawe LP model has more than 6,500 variables and nearly 7,000 equations for the EU single region configuration, and is more than 10 times bigger for the EU multi-region configuration, specialised software developed and commercialised by third parties is used to run LP models.

Generally, this software has three main features: an input interface where the LP developer/user creates and builds the model and introduces the input data to run the model; an optimisation algorithm that solves the mathematical problem (a matrix formed by equations as rows and variables as columns, where the intersections are simply the coefficients that apply to unknowns or variables in each equation, which are part of the input data the user provides); and an output interface that allows the user to visualise and manipulate all the data generated in the solution.

History of the LP model in Concawe

Concawe has been using refinery LP models for more than 30 years, evaluating various topics and subjects that were important to the refining industry at the time, some more practical such as the effect of the evolution of the refined product demand,[3,4,5] and others more theoretical such as the implications of producing a notional high-octane petrol grade[6] to improve engine efficiency and thus CO_2 emissions.

In 1989, a Concawe LP model was used to assess the impact of limiting the benzene content up to 1% volume in gasoline[7] and sulphur content up to 500 wppm in diesel fuel.[8] Thereafter, in 1999 it was used to anticipate the implications of changing gasoline and diesel fuel characteristics[9] given in the Fuels Directive (98/70/EC),[10] where aromatic content in gasoline was limited to 35% volume and sulphur in diesel up to 50 wppm.

After a European Commission consultation in 2000 to reduce the sulphur content of petrol and diesel fuels even further (up to 30 or 10 wppm), Concawe estimated, by using an LP model, the consequences for the EU refining industry in terms of additional costs as well as CO_2 emissions.[11] This study was updated in 2005.[12]

For the maritime sector, Concawe has analysed the evolution of the legislative measures adopted by the International Maritime Organization (IMO) since the introduction of 'sulphur emissions control areas' (SECAs) in 2006, [13,14] up to the implementation of a sulphur cap of 0.5 wt% in the high sulphur bunker fuel specification in 2020.[15]

Another important use of the Concawe LP model has been estimating the CO_2 emissions associated with the production of individual oil products, where Concawe developed a new methodology to produce a consistent set of CO_2 intensities for all refinery products.[16]

In the coming months, the Concawe LP model will be used to carry out a techno-economic assessment of the economical impact for our industry of the reduction of aromatics and naphthalenes in the production of fossil jet fuels in the EU-27 + 3[1] refining system, and, within the framework of the Refinery 2050[17] study, it will help to assess how much low-carbon fuels can be blended into transport fuels while meeting the required commercial grade quality.

[1] The 27 member countries of the European Union plus Norway, Switzerland and the United Kingdom.

Characteristics of the Concawe LP model

The Concawe LP model has been developed in-house from the outset, using internal know-how with the support of Concawe member companies and the help of third parties, such as technology providers and consultants, who have provided some of the immense amount of input data that an LP model demands. Every aspect of an LP model—the relationships, equations, variables, constraints, etc.—have to be input and set by the developer/user; the LP optimiser algorithm only solves the mathematical problem.

The model features a full library of refinery process units represented by a number of operating modes including feedstock type, product yield structure, utilities consumption and all relevant quality parameters. From this information, a refinery can be modelled with any combination of process units.

A range of crude oils is available, representing the diversity of grades available to EU refiners.

A blending module allows finished products to be prepared according to the required quality specifications from selected intermediate streams.

In the Concawe LP model, there is the capability to run as a single EU region (all EU refining systems aggregated into one single large refinery model) or to run in multi-region mode, where the EU is divided into nine regions (see Table 1), each region represented by a single refinery having the aggregated capacity, crude intake, process configuration and product demand of all physical refineries in that region.

The number of nine regions is a trade-off between granularity of results and the anonymisation of individual sites/refineries, making it impossible to identify any specific refinery or refining company from the outcome of the LP model.

Table 1: Concawe LP regions and countries

LP region	Countries
Baltic	Denmark, Finland, Estonia, Latvia, Lithuania, Norway, Sweden
Benelux	Belgium, Netherlands, Luxemburg
Germany	Germany
Central Europe	Austria, Czech Republic, Slovakia, Poland, Hungary, Switzerland
UK and Ireland	United Kingdom, Ireland
France	France
Iberia	Portugal, Spain
Mediterranean	Italy, Greece, Malta
South-East Europe	Croatia, Slovenia, Romania, Bulgaria, Cyprus

Aggregated LP models are expected to over-optimise in the sense that such a model considers the entire region as a single site refinery, allowing the transfer of streams between units without considering the logistical constraints that exist due to refineries being in different locations. To address and minimise this issue, the Concawe LP model is calibrated to match the operation of a particular single year, representing the regional operations at a macro-level for another reference period as long as there are no material differences in the available installed unit capacities, process technologies, global crude balances and regional product qualities. Necessary adjustments would be made for a different reference period if the changes in these aspects of model calibration are known to be significant.

Upgrading the Concawe LP model structure

Until recently, the Concawe LP model has been completely linear, meaning that each feedstock had its own set of yields and stream properties in each process unit and along the model; this made the introduction of a new crude, process units or feedstock highly data- and time-demanding.

Faced with the need to incorporate new feedstocks and processes such as lipid co-processing or bio- or e-refineries, Concawe undertook a complete rewrite of the LP model from scratch to provide it with greater flexibility and adapt it to the latest LP techniques.

The new LP model retains certain features of the previous model, such as having all conventional refining processes modelled to allow for different refinery schemes, the capability to run in EU single- or multi-region mode, and the unique ability to estimate the carbon, hydrogen, sulphur and nitrogen balance in each stream and model unit process, which enables estimation of the CO_2 intensities of the products.[2]

The introduction of pooling structures in the new LP model allows the number of streams to be reduced, for example in the hydrocracker unit, there is now a single feedstock stream, which is the output of the hydrocracker feedstock pool that aggregates all streams that were previously going individually to the hydrocracker.

Another LP technique that has been implemented in the new LP model, which couples perfectly with the pooling structures, is the delta-base modelling, where the yields of a process unit can change linearly according to certain parameters of the feedstock (i.e. the hydrogen consumption in a hydrotreatment unit will increase if the sulphur content of the feedstock is higher than a base case).

With these two techniques, the new LP model is more flexible and adaptable than the previous one. However, it increases the complexity of the model/matrix with more equations (relationships between variables) and non-linearities (a variable multiplied or divided by another variable, as is the case in pooling schemes). Nevertheless, these issues can be addressed by the current LP software packages that include mathematical techniques such as 'distributive recursion', a non-linear technique used to model non-linearities by approximating them with linear segments, which are presumed in advance. An 'LP matrix' is then updated after every recursion. The updated LP matrix is considered to give a sufficiently good approximation of the non-linear model when the differences between the presumed and the real values of the variables are within predefined tolerances.

New features for the upcoming energy transition.

Other new features have been incorporated in the new Concawe LP model: similar to estimating the carbon balance in each stream, it will now be possible to estimate the bioenergy content of the products and intermediate streams to assess how to comply with the policy targets set in RED III, ReFuelEU Aviation[2] and FuelEU Maritime.[3]

Co-processing is also included, focusing on three insertion points in the refinery configuration (distillates hydrotreater, hydrocracker and fluid catalytic cracking units),[18] using data from the literature and complemented with third-party databases.

Green hydrogen and carbon capture are expected to play a key role in decarbonising refinery emissions in the near future, hence a simplified model of an electrolyser as well as a carbon capture plant have been included in the LP model as a representation of these technologies.

Biorefineries are characterised in the Concawe LP model by the main known processes and technologies that currently have enough data to be modelled: lipids to hydrotreatment (HVO[4]/HEFA[5]), biomass to gasification/FT /hydrocracker, pyrolysis (biomass) to hydrotreatment, e-fuels (hydrolysis/carbon capture + FT/hydrocracker) and alcohol to fuels.

Needless to say, the Concawe LP model is one that will be adapted and modified to meet the demands of each study, and will therefore evolve as the fuel manufacturing industry does.

Most of the data used to build the new Concawe LP model comes from the previous LP model as well as from literature and third-party databases, while Concawe member companies have helped fine-tune these data to provide the most representative values of the current practice in the industry.

What to expect from the Concawe LP model?

The output of the LP model is a complete, unit wise, material balance in weight of all refinery units, comprising the unit capacities available and utilised, the feedstocks available and used for processing or blending, the utilities (fuel, electricity, steam) consumption for all processing units and for the overall refinery, as well as the blend composition of all products and the properties of blended products, and an economic summary including the cost of crude, other feedstocks, utilities consumed and the prices of blended finished product.

[2] https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation_en

[3] https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_en

[4] Hydrotreated vegetable oils

[5] Hydroprocessed esters and fatty acids

Sometimes, the output of the LP model is not intended as the final target of the study but rather serves as an intermediate step for further calculations, for example the marginal CO_2 intensities of refined products.[2]

Ultimately, when developing and running LP models, there are two unwritten principles among the LP community that have to be considered. First is the concept of 'garbage in, garbage out', used to express the idea that incorrect or poor-quality input data will produce faulty output data, and second is that the LP is a tool but the LP user is 'THE' tool, meaning that the user is responsible for the input data treatment and output analysis, and the rest is just mathematics.

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