METHODOLOGY FOR THE OPTIMAL DESIGN OF A UTILITY NETWORK IN AN ECO-INDUSTRIAL PARK (EIP)

Article

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Abstract

The aim of this project is the optimization of an Eco-industrial park through innovative methodologies. I have been working in a chemical laboratory, performing a stage, in order to support a PhD student's thesis. Most of the time I have been working with computer simulations and some of the information obtained are not shown in this report. Additionally, my work has been based on writing an article, what is presented in this report, to explain the methodology used for the design of an Eco-Industrial park, as well as the case study. As you will see, the article is not completed and some parts have been eliminated. This parts are those related to the optimization process, where the PhD student is working and is not finished yet. For that reason, it is better not to not present some results that may be wrong or incomplete. Anyway, in some months, this article will be completed and published.

Introduction

Nowadays, the depletion of the natural resources has increased because of the rising industrialization and urbanization during the last decades. In the 80's, the idea of "sustainable development" has emerged (Brundtland, y otros, 1987), whose aim is to reach the environmental preservation while increasing the business success within the industry. From here, a new concept called industrial ecology was popularized by Frosh and Gallopoulos, in 1989, as an attempt to reduce the pollution, natural resources consumption, and wastes while maintaining the production levels and optimizing the use of energy and materials. This idea is directly related to another concept: the industrial symbiosis, which involves "separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products" (Chertow, 2000), but a geographical proximity between the participating facilities is essential because the transport of the waste material is too expensive. This is the case of the eco-industrial parks (EIP) defined as "an industrial system of planned materials and energy exchanges that seeks to minimize energy and raw materials use, minimize waste, and build sustainable economic, ecological and social relationships" (Boix and al., 2015; Alexander et al., 2000). In this way, what was typical a waste for a facility, now could be a value input. The participating industries have the common capacity to convert, among chemical and physical processes, the raw materials into (by)products, involving industries such as energy, chemical, steel or aquaculture, for example (Zhang and Strømman, 2008). The condition of economic viability for a park is to prove that the benefits obtained by each company working separately are lower than those of each one working collectively (Boix and al., 2012). The problem in this field, noticed by Zang and Strømman, is the slow, but spontaneous evolution of resource exchanges between facilities, realized, for example, in Kalundborg industrial symbiosis in Denmark, a successful case of EIP. When the possible exchange between two companies is discovered, the plan and design process is too slow to have a substantial impact in our society (Zhang, Strømman, Solli, & Hertwich, 2008). That is why it is necessary to develop a systematic and general procedure to reach the exchanges integration.

The most studied way to design an optimal EIP is to create, within the park, networks that exchange materials, water and energy. Commonly, the optimization is performed independently for each type of network (Boix and al., 2015), but the real aim is to reach the simultaneous optimization of all the resources to attain with environmental objectives as well as economic and social ones. As noticed before, the interaction between the different networks is essential to increase the symbiotic relations. Due to the antagonist goals of the EIPs, an optimal configuration where each company has a positive gain while preserving the environmental conditions, is difficile to achieve. Though the optimization, one or more objective functions can be defined by following some constrains, but in the design of an EIP, the multi-objective approach is the one that can better satisfy the EIP requirements. However, in 2015, Boix and al. have noticed a lack of multi-optimization studies. Due to the work done by Montastruc and al. in 2013, in which is tested the design flexibility of an EIP by changing a few parameters of one plant, they have realized, the impossibility of an optimal EIP design in this way. Later, in 2015, Ramos and al., proposed a type of multi-objective optimization by using goal programming. This type of optimization allows to include some slack or surplus variables to represent the deviation from the objective by eliminating some objective functions, in this case that could represent changes in some EIP plant. Thus, they proved its feasibility as a method to design industrial water networks. Another alternative, proposed by Boix and al. in 2015, is the game theory, defined as "the study of mathematical models of conflict and cooperation between intelligent rational decision-makers" (Myerson, 1991). But in the particular case of EIP, they proposed the concept of Nash equilibrium problem, in which non-cooperative players, enterprises in this case, make their best strategy to maximize/minimize its own benefits/costs knowing the other's strategies, and no player has anything to gain by changing only their own strategy (Osborne & Rubinstein, 1994).

Methodology

1. EIP model definition

To achieve the most accurate optimization of the EIP, it is necessary to quantify the interactions between facilities, as well as the mass and energy requirements. To this end, the method proposed by Casavant and Cote using chemical process simulation is applied. The aim of this study is not the creation of a new EIP per se, but the design of utility networks by using optimization. Therefore, it was decided to base the park on a previously studied EIP. Thus, the case study is not an imaginary situation, but a real proposed industry set in a real place which has its own requirements and restrictions. Based on this, the activities carried out in the studied park have been established, taking into account the environmental and social conditions and geographical location. In addition, specific needs and material balances defined in the model were used as a reference to our simulations.

2. Simulations, results analysis and comparison

All the EIP members must be simulated as closely as possible as the EIP desired. For that purpose, it was used the French software ProSimPlus. This tool allows chemical and physical processes simulation, including all types of required units in the chemical industry, such as distillation columns, reactors, absorbers, etc.

Before starting with the simulation procedures, an analysis of every EIP activity with their correspondent units must be completed. It should include both a schematic flowsheet and a global mass and energy balance. Also, raw materials, process conditions and inlets, have to be defined. The thermodynamic model, as well as simplifications and hypothesis should be defined in this step. In our case, all processes should be simulated with a set of unit operations to facilitate the construction of the flowsheet.

For each process simulation is necessary to collect all the data for every current: pressure, temperature, flow, molar and mass composition, etc. Through them, we can analyze if all the processes are running as expected and make a comparison with the article purposes. If results obtained are far from the EIP model, will be necessary to modify some of the modules specifications, flows, temperatures, etc.

3. Define the number of participating companies and their internal processes

Now, the number of companies that will take part in this EIP must be fixed but, previously, it is necessary to determinate all the flows, inlets and outlets, circulating around each unit, as well as their destinations units. In this way, the entire EIP is interconnected and is easier to determinate the different companies with this global view. For us, each company is defined as a black box with their corresponding inlets and outlets. A company can be comprised by one or a group of the simulated units. Thus, each company will perform some of the necessary EIP activities and have a defined number of intern processes that will exchange energy. As a result, it is obtained an EIP flowsheet that shows the participant members, material and energy flows and the number of internal processes that will exchange energy.

4. Utilities definition

Once defined all the processes, it is necessary to introduce the utilities that will allow energy exchanges occur. A utility, is understood as a countercurrent flow that produces a cooling or heating in the main stream. As it is known, each utility works in its own temperature range, but the processes can take place in any temperature, so it is necessary to find the appropriate utility for each one to prevent the crossed profiles.

The majority of exchanges take place at the same temperatures zone; hence, there are four typical utilities used: cool water (to cool) and HP, MP and LP steam (to heat). Nevertheless, there are some processes out of the ranges of temperature of the standard utilities. Then, an alternative must be found. For example, if the exchange occur in a very low temperature, a refrigerant could be useful or, otherwise, if heating is really high, a fired heater may be used. After this selection, a list of the utilities with their operating temperature ranges is specified and, through it, the most appropriate utility can be assigned to each process. Due to that, the amount of energy required for each company can be estimated.

5. Optimization: Goal programming and Nash equilibrium

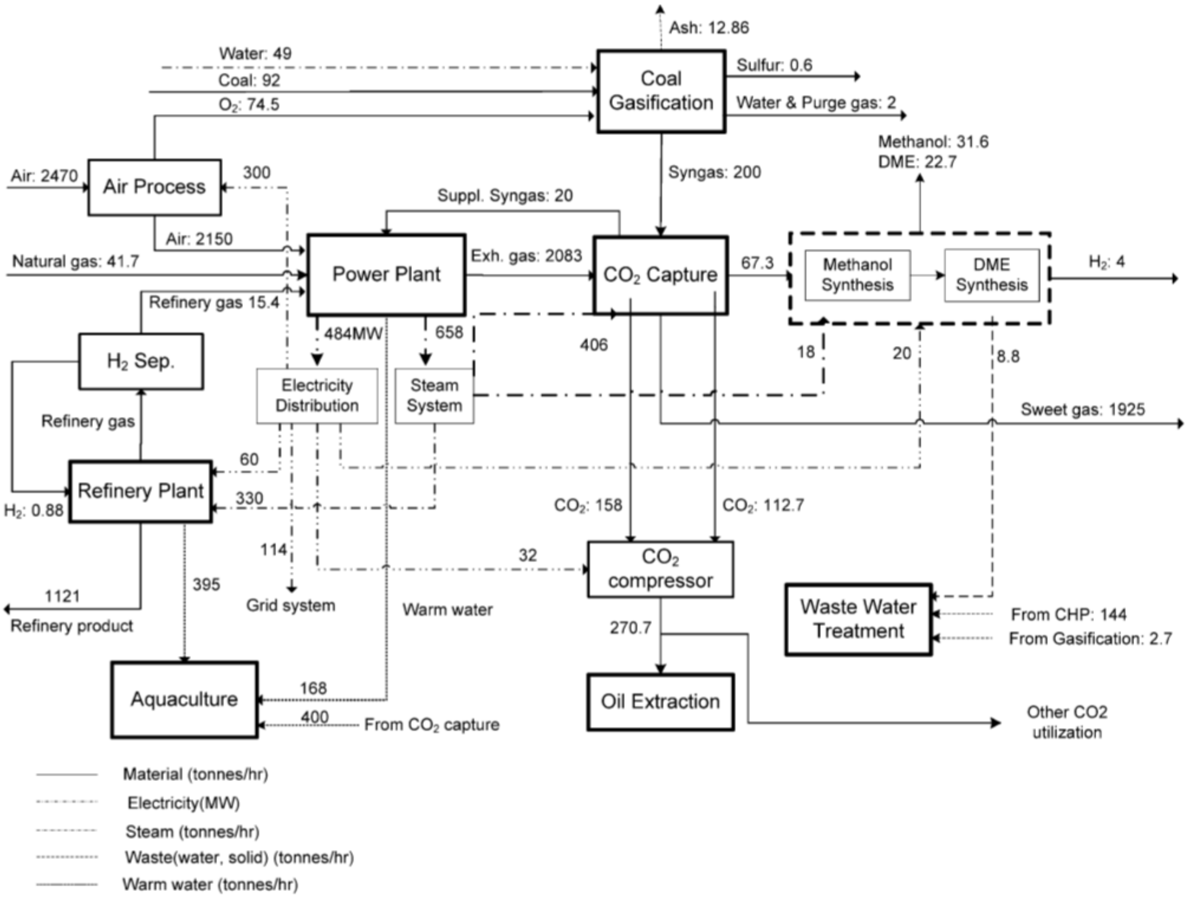
PhD student

Case study

Based on the EIP proposed by Zhang and Strømman, in 2008, as a reference, it was designed a model adapted to our utility network optimization project, always trying to guarantee the maximum similarity to ensure a greater degree of reality in the study. The article specifies that some of the modules are already built while others are under construction or conception and design so, it is not an existing park, but has the potential to become. Choosing this model, it is already defined an environmental, social and territorial context to the problem statement.

The planned EIP is located in Mongstad in western Norway. Currently, only the refinery plant and some gas processes, are already existent. Also, the proximity of a port and some underground storage tanks, are relevant to search new potential activities. As it is known, the principal refinery products are petrol, diesel and other light petroleum products so, the principal feedstock is the petroleum. Unfortunately, oil fields of the North Sea are being depleted and that, will clearly influence the future business of refining and fuel supply. Environmental policy is becoming more strictly and narrowly, especially with the CO2 and other contaminants emissions. The creation of a combined head and power plant (CHP) could be an important step for this industry. It could be a big energy supplier, not only for the park, but to export it. In addition, this facility may produce the high-pressure steam needed to the refinery and CO2 that could be also, reutilized in the refinery. Even so, it would be essential to reduce the CO2 emissions through a CO2 Capture (a further park activity). An additional advantage of building this two facilities is the low temperature heat produced. Conversely, high temperature waste heat the fjords, which is not permitted by the authorities.

In the flowsheet proposed by the Norwegian team, all the mass and energy flow are classified and



described. Centered on them, the needed simulations were performed. In this way, each module can be described and analyzed independently and later, the obtained results can be compared with the original case.

Figure 1: General flowsheet of the Norwegian EIP

The main activities were selected to be part of our EIP, understanding as a main activities, those in which their internal processes, as well as energy exchanges and mass flows, are relevant for the proper development of the park, such as the refinery or the power plant. There were omitted modules as water treatment or aquaculture. This decision stems from the fact that, in overview, these processes do not make significant changes in energy optimization. In addition, the chosen modules, generally, do not involve complicated bioprocesses and can be simulated with simple units, reactors, distillation columns, etc. The selected activities for this study were: Coal Gasification, CO2 Capture, MeOH and DME Synthesis, Refinery Plant, Power Plant and Air Separation.

Coal Gasification

This part of the process consist in the transformation of coal into a synthesis gas (H2 + CO). The coal gasification is the beginning of the synfuel production which consist of coal gasification, CO2 capture, and fuel synthesis (in this case methanol and DME). Further, this process allows the option of using the syngas produced as a supplementary fuel in the power plant to gain the advantages by introducing a Duct Burner for a supplementary firing, as explained by Zhang and Strømman.

The EIP proposed by Zhang and Strømman, was not enough to develop all the coal gasification simulation, we did not know exactly the internal structure used for the simulation nor the requirements and conditions they had considered. Therefore, it was searched another complementary referent. In 2012, the Colombian researchers Preciado, Gonzalez-Rivera, Ortiz-Martinez, Sierra-Ramirez and Gordillo worked on a process simulation similar to the Norwegian team, making also assumptions based on a Fischer-Tropsch process and other techniques to separate the sulfur from synthesis gas. Thus, using the known information from the article published supported by the simulations of the Colombian team, we obtained the coal gasification process.

This procedure was set up in two parts as recommended by the article. The first one consisted of an equilibrated reactor in which some of the pyrolysis and all the combustions were achieved using as feedstock steam, oxygen and coal. The other, consists of a water shift reactor (WSR) where the ration of H2/CO in the synthesis gas would be defined. In order to simplify the simulation, the gasifier and water shift reactor are assumed to be equilibrated reactors. This, can be applied because almost all the combustions and water shift reactions proceed rapidly to a very near equilibrium state. The thermodynamic properties were calculated using the Peng-Robinson equation of state, as specified in the Norwegian article. It is the most common model to use for complex mixtures such as petroleum fluids, natural gases, crude oils, and heavy oils, etc.

As proposed by the article, surat coal was selected as feedstock for the gasifier (carbon: 37.4%, volatile matter: 40.0%, ash: 14.0%, moisture: 8.0%, sulphur: 0.5%, nitrogen: 0.1%). For us, the ash in the coal was considered to be an inert constituent, so it was not included in the simulation, and we considered to be 50% n-pentane and 50% n-hexane. The gasification reagents were oxygen and steam coming from the HRSG. The final composition of the syngas depends significantly on the operating conditions of the gasifier. In this case, the Fisher-Tropsch process (van Dyk, Keyser, & Coertzen, 2006)was used to design requirements.

As an improvement, we introduced a water recirculation process. In the first proposal, a big amount of fresh water was introduced and, consequently, there were too much waste water leaving the system, but analyzing the residual water composition from the dewatering unit (99,99% water), it was assumed that it was pure enough to be utilized as a feedback in the water flux. Through this change, a big amount of clear water could be saved.

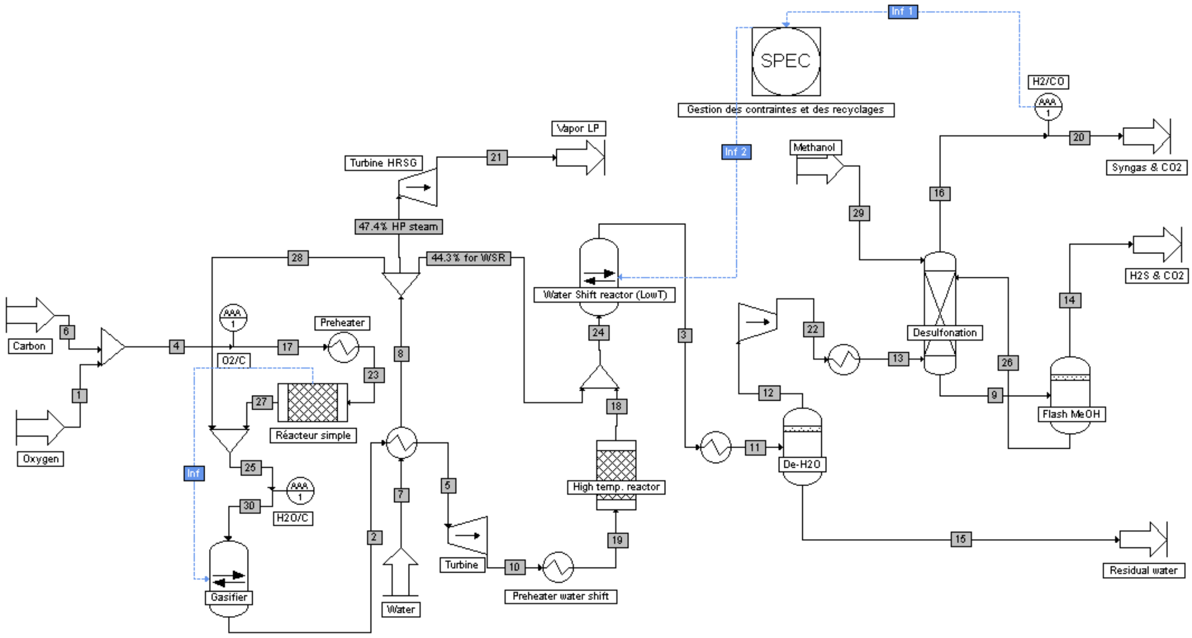


Figure 2: Process flowsheet for the Coal Gasification

Process:

The three components, coal, oxygen and steam, are feed in the gasifier to produce the first raw syngas. The reactions taking place in this unit were obtained by the Colombian article (Preciado, Gonzalez-Rivera, Ortiz-Martinez, Sierra-Ramirez, & Gordillo, 2012). Later, raw syngas goes through a heat exchanger which is part of the HRSG. This unit transforms the incoming water into steam that is divided in 3 different streams; one, as feed of the first reactor (gasifier), another as feed of the second reactor (WSR), and the third, into a high pressure turbine for electricity production were it would reach a low pressure.

The second equilibrium reactor, the WSR, performs the hydrolysis of the carbonyl sulfide and the water shift reaction (to produce H2, CO2 and CO) ensuring, with a specification, that molar ratio of H2/CO of syngas will be approximately 3. Subsequently, in the dewatering unit, is performed the elimination of the biggest part of residual water. Finally, the clear syngas is acquired by the desulfonation unit; Methanol and dry syngas are introduced to the absorption column but, as a result, methanol, H2S and other contaminants are generated. Furthermore, a flash module is placed to separate a fraction of the wasted methanol to make it recirculate into the desulfonation unit.

CO2 Capture

Nowadays there are lots of CO2 removal methods. The proposed by the Norwegian team was the chemical absorption with amines. It needs a lot of energy regenerating the solvent but is able to extract more CO2 than others, also it has a high degree of technological maturity.

The simulated CO2 capture consists of an absorption column and a renovation column with a solvent recirculation. Following model of the Norwegian's article, this solvent is a solution of Diethanolamine (DEA) and water, at a concentration of around 28% of DEA and some traces of carbon dioxide which comes from the atmosphere, the latter were included in the simulation to represent as best as we can the reality of the process.

The proposed EIP includes two CO2 captures; one for the syngas from the coal gasification gas and one for the exhaust gas from the power plant. There were no differences between the two processes, only the quantity of solvent, due to the differences between the amounts of syngas and flue gas introduced. The thermodynamic properties were also calculated using the Peng-Robinson equation of state.

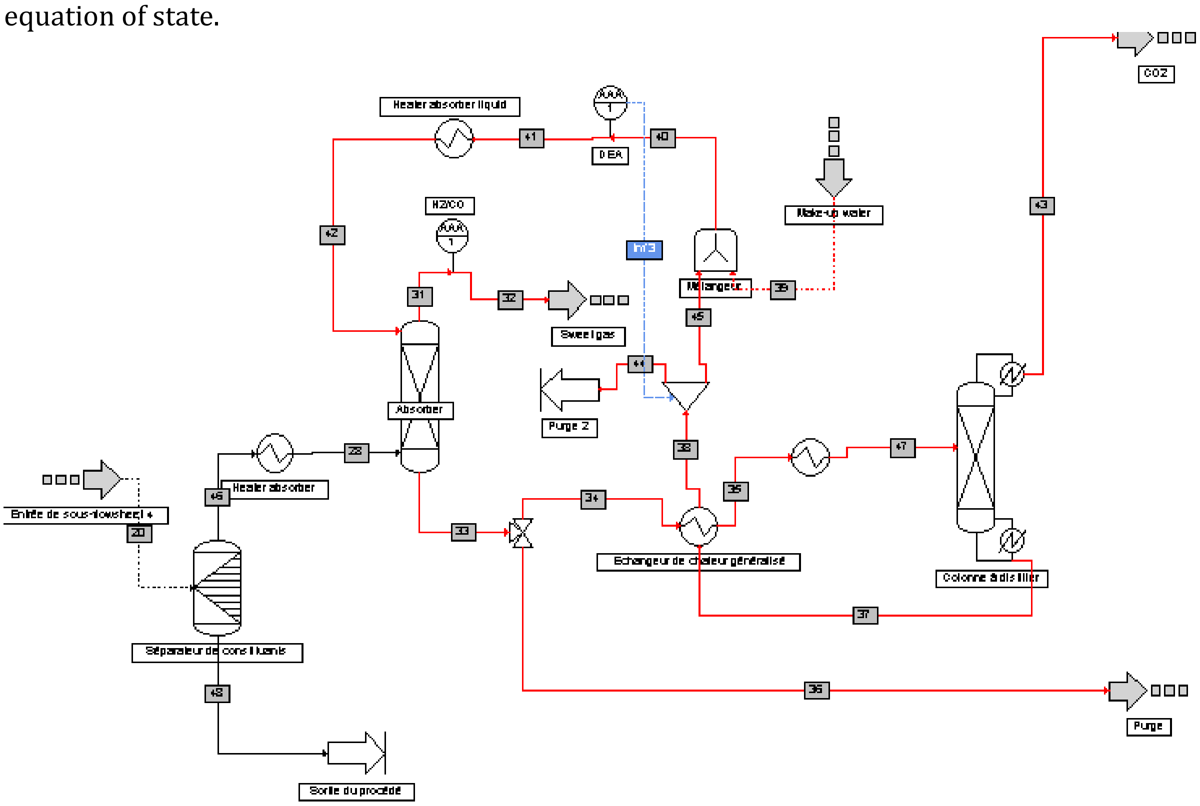


Figure 3: Process flowsheet for the CO2 Capture

Process:

The syngas/exhaust gas goes to the constituent separator, where some unwanted components from the coal gasification/power plant were eliminated. Then, the clear syngas arrives to the absorption column, in which the transfer from the gas phase carbon dioxide takes place into a liquid solvent. The gas contacts with the solvent in countercurrent, and from that reaction the purified gas is separated to the rich solvent which is removed from the bottom and sent to the distillation column. In this unit, the solvent can be restored and recycled to the absorber. From the top of the distillation column the desired CO2 is obtained.

MeOH and DME Synthesis

As explained by Zhang and Strømman, the dimethyl ether has become an alternative fuel to diesel or liquefied petroleum gas and also it is easily transported. In the automotive sector is a potential alternative because of "the low emissions of NOx, SOx and hydrocarbons, near-zero fumes and lower engine noise as compared to the traditional diesel". That is why an EIP could be interested on its production.

Again, this activity is divided into two: the methanol synthesis and the DME synthesis. The first one is implemented by an equilibrated reactor followed by a flash unit. The needed reactions for this process were obtained from the work done by Chang, Rousseau, & Kilpatrick in 1986, and the Soave-Redlich-Kwong thermodynamic model was used. To perform the DME synthesis, a simple reactor with two distillation columns were defined. For the DME reaction, was employed the methanol dehydration process with Al2O3 as catalyst (Mingting, Lunsford, Goodman, & Bhattacharyya, 1997). In this case, the UNIQUAC thermodynamic model was chosen because of the two distillation columns.

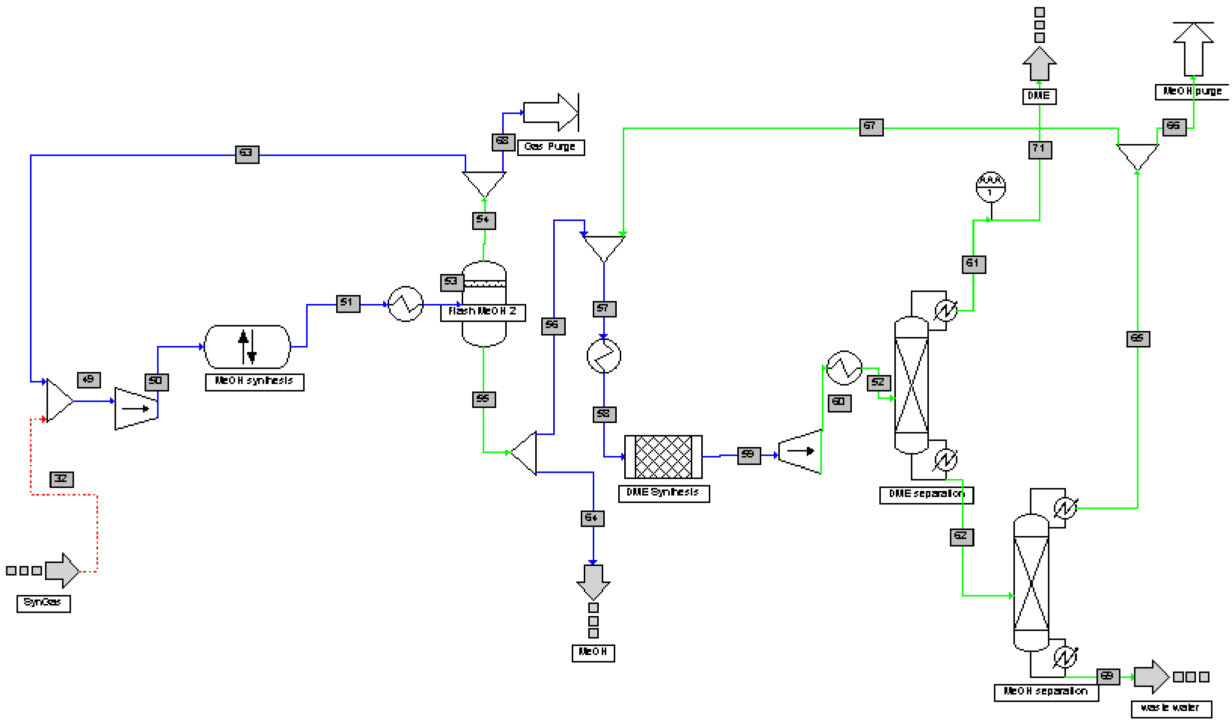


Figure 4: Process flowsheet for the MeOH and DME Synthesis

Process:

The mixture of H2, CO and CO2 from the CO2 capture enters to the first reactor where the methanol synthesis takes place as well as the water gas shift reaction (to produce CO and H2O). Subsequently, in the flash unit, the light gases are separated easily from the main liquid products (methanol and water) and recirculated for a better conversion yield. At this point, a fraction of the methanol is stored for its purposes and the other remains on the process and arrives to the second reactor, where the methanol dehydration is produced. Finally, we found the two distillation columns; the first one used to separate the most of the pure DME from unreacted methanol and water, and the second, to separate recycling methanol from waste water.

Refinery Plant

The objective of the refinery plant is to separate and produce complex mixtures called petroleum products from crude oil, where are included several classes of fuels, asphalt, paraffin wax, lubricants etc. To make this process possible a series of reactors, one distillation column and one vacuum distillation column were needed. The thermodynamic model used in this case was the Peng Robinson's model as being the most used when working with petroleum oils, as explained above.

The procedure for a good distillation of the crude oil is dependent of the composition of the feedstock. Every refinery has its own proper specifications when it comes to the desired product. In general terms, all the products obtained differ on their boiling point and thus, can be recovered from different heights of the tower. In order to simulate the fractions of the products it was necessary to divide the process in atmospheric and vacuum distillation.

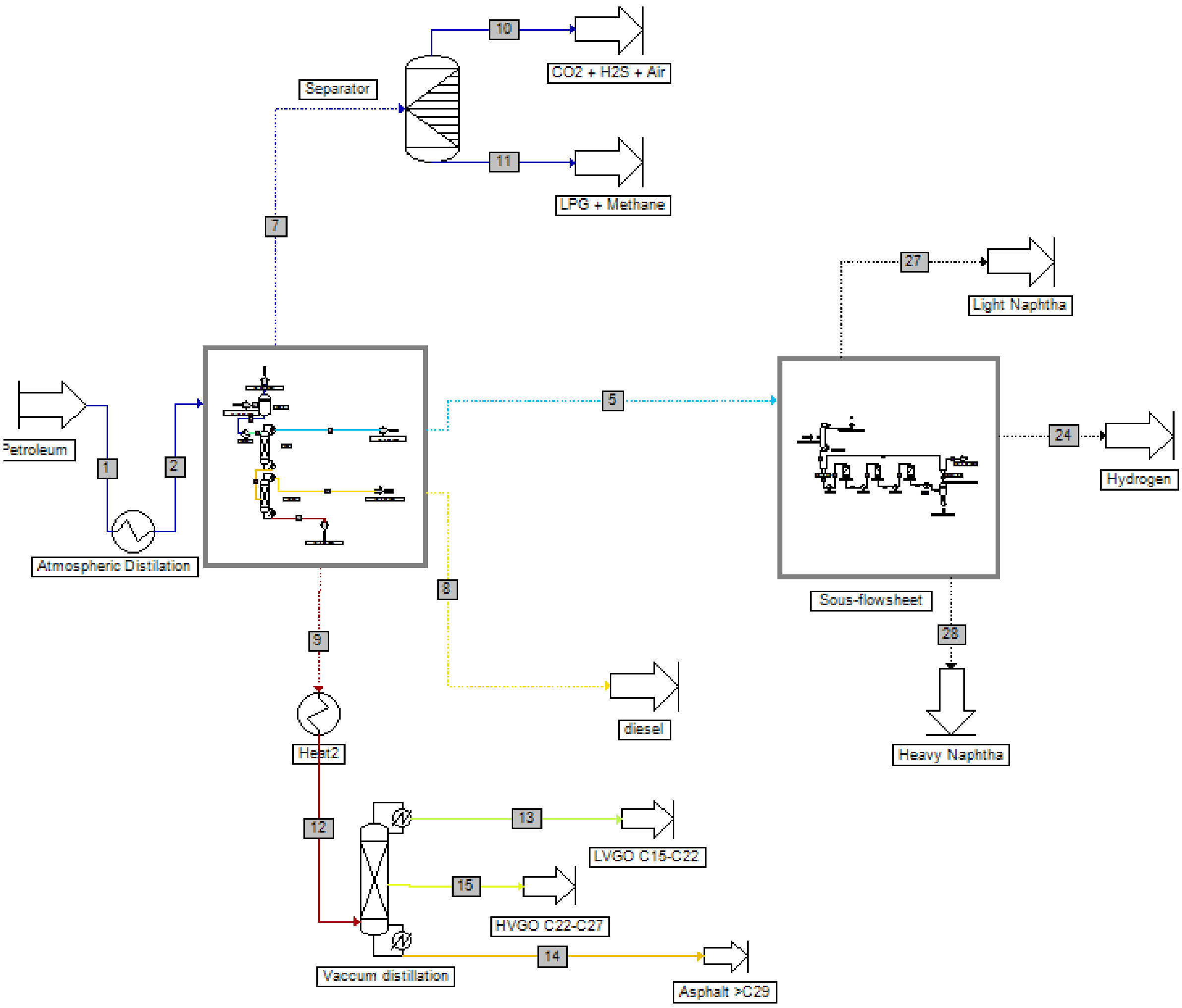


Figure 5: Process flowsheet for the Refinery Plant

Process:

In the atmospheric part a use of two-phase liquid-vapor separator was needed for the components of light hydrocarbons that are gas at room temperature and gases such as N2, H2S, CO2, and air. The residue from the two-phase liquid-vapor separator was the inlet for the first distillation column which was used to separate the naphtha from the heavier hydrocarbons like diesel and kerosene and immediately afterwards a second distillation column to divide de diesel from the heavier hydrocarbons. For the next fraction it was necessary to make vacuum distillation in order to separate the hydrocarbons from C12 to C22 (as the lightest), C22 to C27 and everything over C29 as residue and which was considered as asphalt.

Naphtha reforming has an important role in the petro chemistry industry. The core of this process is consists of three or four fixed-bed adiabatically operated reactors in series. The feedstock is mixed with a recycled gas stream containing 60 – 90 mol% hydrogen which is heated again. The other product is named reformate which is blended for gasoline purposes and can be treated accordingly to the desired products of the refinery. Each reactor was made for a different process in the refining, the first one was made to simulate the dehydrogenation (Turaga & Ramanathan, 2003). The next reactor was used to make the isomerization and the last one was used for the hydrocracking process where the alkanes are broken into lower alkane chains thanks to catalyst that is usually used and to saturate these lower alkenes chains hydrogen from the same process is recycled in order to saturate the fractioned alkanes hence the consummation of hydrogen.

Power Plant

The power plant will be the main energy and steam supplier in this EIP, therefore is one of the most relevant unities. The big amounts of energy produced will be distributed among the other facilities participating in this park. Thus, all companies will be linked, and that favors the symbiosis within the park.

For the design of this one, a gas turbine was used to produce most part of the power. It uses a mixture of natural gas (troll gas) and the gas from the refinery as feedstock, following the article. In this step, were also introduced air, from the air separation unit, which was advantageous for the combustion process. Due to the work done by Ivar S. Ertesvag, Hanne M. Kvamsdal and Olav Bolland, in 2003, fuel and environmental requirements were defined, as well as the gas turbine conditions.

Supplementary firing is one of the post-combustion processes employed to improve the power plant and gain some advantages. This complement produces, inter alia, an augment of the exhausts gas temperature without changing combustion conditions. Additionally, firing carburant again, will increase the quantity of CO_2 in flue gas and that could be a benefit for the following processes, as the CO_2 Capture. In our case, the feedstock carburant was the part of the syngas, coming from the Coal Gasification, not used in the MeOH and DME synthesis.

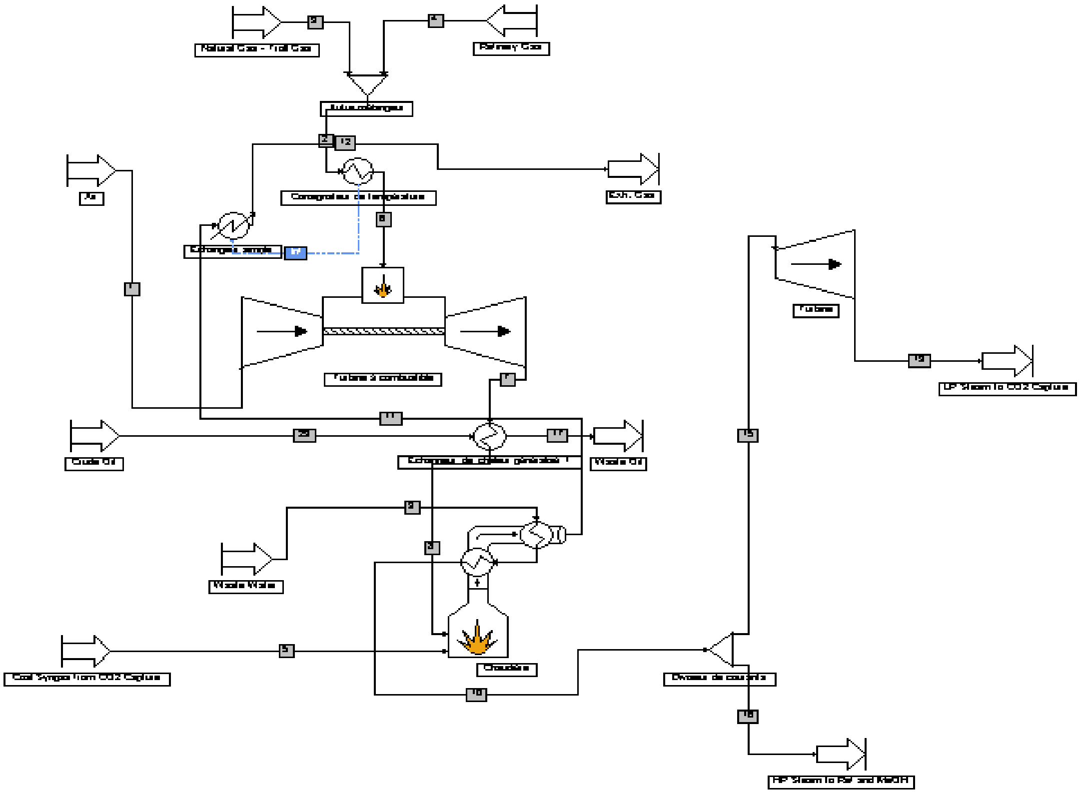


Figure 6: Process flowsheet for the Power Plant

Process:

The mixture of natural gas and refinery gas enters, together with the pre-compressed air, to the gas turbine to produce both energy and exhaust gas. Afterwards, this gas preheats the crude oil for the refinery plant, and later is fed in the boiler with the syngas to generate the supplementary firing. Subsequently, the flue gas arrives to the HRSG where, though the introduction of boiled water, an energy exchange takes place. At this stage, the remaining exhaust gas is recirculated to heat the natural gas, and sent to the CO2 Capture. On the other hand, it is obtained the high-pressure steam desired to supply the EIP, but lack the low-pressure steam, which is achieved by adding a steam turbine at the end of this process.

Air Separation

Nowadays, many oxygen separation methods are discovered. Initially three different technologies were contemplated: Pressure swing adsorption process (PSA), which uses the adsorption with zeolite as an alternative to the liquefaction; membrane technologies, which the gas can be separated by synthetic membranes and it is also a non-cryogenic process and; cryogenic distillation process, which needs the liquefaction to be implemented. The first two methods are usually used to produce relatively small amounts of air separation, in particular, the PSA process is commonly used in hospitals. By contrast, the cryogenic process is the most used method in industry by producing higher amounts of production, ensuring the required purity. Hence, we thought that the third method fits better into our project.

In 1998, Cornelissen and Hirs made a simulation of a cryogenic distillation process in a real plant, performed by the software Aspen Plus, which we used as a reference for our project. As they proposed, the activity involve two distillation columns; low and high pressure columns.

Process:

The pre-compressed air is cooled by two heat exchangers to reach liquefaction, about -174 ° C and enters to the low pressure column. In this unit, a portion of the nitrogen, in liquid state, is separated from the remaining mixture, oxygen and nitrogen, which will flow out through the bottom of this column and will reach the high pressure column. Here, liquid oxygen will come out from the column being completely separated from nitrogen.

Participating enterprises

Once obtained all the simulations and having interconnected the entire EIP, the construction was completed. Then, was easy to recognize each module with its internal processes and its inlets and outlets flows. Therefore, was possible to carry out the enterprises selection. As the Norwegian model was already divided into units and we found it a logical classification, we decided to conserve it and continue with the feasibility of the study. Thus, every activity was become an enterprise. The only exception was the two CO2 Captures that were considered as a single company, owing to the fact that they work on the same process. As a result, six enterprises would participate in this EIP.

Prior to the optimization, it was required to know what were the processes involved in energy exchanges, as well as the amounts of energy required. In this work, the useful processes for the utility network optimization are those which need an external contribution to produce the energy exchange. The clearest case would be a simple heat exchanger, which must increase or decrease a stream temperature. Moreover, condensers and reboilers of distillation columns or equilibrium reactor, required a supplementary utility too. In contrast, an adiabatic reactor did not need any utility to run, as well as turbines, compressors or combustion chambers, for example. But this are not defined yet, so when a temperature range is out of the work temperature range of the utilities now considered, the utility used is not specified. We have considered the following utilities, as the typical ones:

Table 1: Typical utilities with its temperature ranges.

Tin (°C)	Tout (°C)	Type
10	15	Cool water
175	174	MP Steam
148	147	LP Steam
335	334	HP Steam

Examining the temperature ranges work of the listed processes of each company, it was defined a number of utilities that complement the energy demand requirement, as well as the utility needed for each case. Characterization of each enterprise detailed below.

Table 2: Enterprises with their processes and the needed utility for each case.

Enterprise	Process	Tin process (°C)	Tout process (°C)	Tin utility (°C)	Tout utility (°C)	Power (kJ/h)	Type
1 COAL GASIFICATION	1	7,29848	1450	-	-	-1,393050E+09	Other
	2	1450	1450	5	10	-1,503504E+09	Water

	3	1424,15	1424,15	5	10	-1,213112E+09	Water
	4	145,313	800	-	-	2,556040E+08	Other
	5	800	800	-	-	315938	Other
	6	879,987	550	5	10	-3,007372E+08	Water
	7	550	20	5	10	-3,874460E+08	Water
	8	222,747	-40	-	-	-1,242420E+08	Other
	9	-29,1771	-29,1771	148	147	3,399352E+07	LP Steam
2 CO2 CAPTURE: SYNGAS & EXH. GAS	1	-15,9664	-15,9664	148	147	238452	LP Stream
	2	-15,9664	25	148	147	1,743700E+07	LP Stream
	3	42,7419	23	5	10	-4,007620E+07	Water
	4	65	80	148	147	4,364490E+07	LP Steam
	5	72,965	70,265	5	10	-2,593060E+06	Water
	6	94,74	101,2	148	147	5,539160E+07	LP Steam
	7	115,541	115,541	148	147	171511	LP Steam
	8	115,541	23	5	10	-3,300180E+08	Water
	9	45,2906	23	5	10	-1,128370E+08	Water
	10	65	80	148	147	1,103290E+08	LP Steam
	11	74,189	70,68	5	10	-2,632820E+06	Water
	12	96,407	100,59	148	147	1,450460E+08	LP Steam
3 DME & MeOH Synthesis	1	197,588	260	5	10	-1,816907E+08	Water
	2	260	23	5	10	-2,442210E+08	Water
	3	23	30	148	147	1,962018E+07	LP Steam
	4	53,2626	300	335	334	5,990900E+07	HP Steam
	5	300	300	5	10	-8,550526E+06	Water
	6	176,158	-22,5817	-	-	-5,267890E+07	Other
	7	-25,055	-25,163	5	10	-1,690050E+07	Water

	8	-15,589	8,7217	148	147	2,667640E+07	LP Steam
	9	-25,086	-25,086	5	10	-4,548730E+06	Water
	10	5,3592	41,292	148	147	9,144440E+06	LP Steam
4 REFINERY	1	40	40	148	147	8500,95	LP Steam
	2	89,1133	40	5	10	-1,799004E+08	Water
	3	40	200	148	147	3,537400E+08	LP Steam
	4	144,2	-55,562	-	-	-2,923230E+08	Other
	5	247,82	285,09	335	334	2,670140E+08	HP Steam
	6	247,87	216,3	5	10	-1,101460E+08	Water
	7	343,88	372,5	-	-	1,570780E+08	Other
	8	372,501	400	-	-	5,739430E+07	Other
	9	232,01	174,02	5	10	-2,470200E+08	Water
	10	301,11	302,44	335	334	2,221930E+07	HP Steam
	11	52,152	40,866	5	10	3,331780E+07	Water
	12	103,59	107	148	147	1,319560E+08	LP Steam
	13	88,0279	503,85	-	-	1,629320E+08	Other
	14	110,086	503,85	-	-	1,502640E+08	Other
	15	514,008	503,85	5	10	-4,000740E+06	Water
	16	512,38	38	5	10	-1,907600E+08	Water
5 POWER PLANT	1	110	250	335	334	1,658360E+07	HP Steam
	2	313,604	335	-	-	2,863890E+07	Other
6 AIR SEPARATION	1	302,626	10	5	10	-1,480080E+08	Water
	2	10	-174,395	-	-	-1,815450E+08	Other
	3	-176,781	-176,788	-	-	-1,128094E+08	Other
	4	-174,33	-172,828	-	-	1,233036E+08	Other
	5	-72,5818	-146,306	-	-	-3,267612E+07	Other
	6	-192,141	-192,143	-	-	-8,776793E+07	Other
	7	-178,89	-178,792	-	-	1,089362E+08	Other
	8	-182,796	25	-	-	4,582907E+07	Other

Goal Programming and Nash equilibrium

PhD Student

Conclusions

PhD student

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