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Life Span Production Plant Optimisation under Varying Economic Conditions

Andreja Nemet[a], Jiří J. Klemeš[b], Zdravko Kravanja[a,*]

[a]Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova ulica 17, 2000 Maribor, Slovenia
[b]Centre for Process Integration and Intensification - CPI[2], Research Institute of Chemical and Process Engineering - MŰKKI, Faculty of Information Technology, University of Pannonia, Egyetem utca 10, 8200 Veszprém, Hungary
zdravko.kravanja@um.si

The economically viable process designs should be, besides other criteria, profitable over entire process lifetime, not only at present time. An improved process design can be achieved by an appropriate trade-off between product income, operating cost and investment. The distribution between the operating cost and the investment is naturally constrained by the utility, raw material and product cost. However, all these prices are varying over lifespan of the process. The appropriate trade-off can only be established correctly if it reflects the future variability and even unpredictability of these cost. The expected impact on the trade-off would tend to compensate the cost variations, for example at higher utility cost a higher investment can be economically viable in order to decrease the operating cost. Similarly, higher raw material cost would tend to increase the efficiency of the process technology, which usually results in a higher investment. Low product price have a similar influence. However, when all the prices are simultaneously considered the tendency of each separate impact can be different. The objective of this work is to optimise process design over entire process life-time by considering some provisions for future cost fluctuations.

The majority of process synthesis models have been single-period considering only fixed current cost. However, the utility, raw material and product costs are fluctuating rather quickly and the optimal process design at certain period of time is different from the design at another period. In order to consider future costs, when synthesizing processes, a multi-period mixed-integer nonlinear model (MINLP) has been developed. Different utility, raw material and product price projections, based on the historical prices, were considered due to the uncertainty of the forecast. As an objective a maximisation of Expected Net Present Value was selected in order to account for the future utility, raw material and product prices, as well as for the time value of the money.

The influence of future utility, raw materials and product prices on the process design can be considered and analysed where simultaneous impact of all those costs on the an overall process performance is therefore explored rather than isolated impacts from individual cost. Furthermore, the distribution of expenditure for investment, raw materials and utilities between the utility system and the production/separation part of the overall process can also be investigated.

The solutions of proposed optimisation methodology seem to be more robust, compared to the conventional optimisation, since it considers future variation of cost. The results of the process synthesis described yield process designs, which have higher probability to meet each time period optimally over their full life-span. Solutions obtained are less dependent on the external price fluctuations, are economically more attractive, and yet more sustainable.

1. Introduction

The annual production of methanol is above 40 Mt and still shows a growing tendency with approximately 4 % increase each year (Aasberg-Petersen et al., 2013). It is used as a feed for production of range of chemicals as acetic acid and formaldehyde amongst others. There are many different raw materials utilised for methanol production as a mixture of natural gas and biomass (Li et al, 2010) or from methane by applying Ammonia-Oxidizing Bacteria (Taher and Chandran, 2013). Also a different approach of

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utilising steel-work off-gases either with of without addition of a biomass for production of methanol has been presented by Lundgren et al. (2013). Despite different possible sources methanol is still mainly produced from natural gas. However the production from coal is increasing significantly, especially in regions where natural gas is not available or is expensive, for example in China (Aasberg-Petersen et al., 2013). Due to the sharp competition between various raw materials - mainly between natural gas and coal - the design of a methanol production plant should be performed considering many aspects. For obtaining an optimal process design a proper trade-off between operating cost and investment should be established. Kordabadi and Jahanmiri (2005) has been used a genetic algorithm for designing a methanol plant under varying condition of the length and temperature of a stage in two stage methanol synthesis reactor. A different approach for process synthesis had been presented some time ago by Kravanja and Grossmann (1990) applying a MINLP model using ProSyn programme. The fluctuations can be handled by mathematical programming approach considering different scenarios. Applying either deterministic approach, where the variations are uniquely determined though known relationships among different states, in contrary stochastic approach applies ranges of values for variables assigning them a probability distribution. Different strategies for handling uncertainties have been proposed (e.g. Novak Pintarič et al, 2013). However, mainly the physical uncertainties or technological (e.g. feed composition, temperature, conversion factor etc) have been studied so far. Other varying parameters, which have a significant impact on an optimal solution, are the fluctuating prices of raw materials, electricity, product and utilities. The prices of these quantities showed significant variations in the past; therefore it is unrealistic to expect constant prices during whole lifespan of a production process. A similar approach has been developed already for the optimisation of distillation columns (Nemet et al., 2012).To cope with those issues a multi-period mixed integer nonlinear programming (MINLP) model has be developed. A stochastic approach has been applied due to the uncertainty of the price forecast and different prices projections have been derived based on historical prices.

2. Methodology

2.1 Process flowsheet

The aim of this work is to optimise the process of methanol production process over entire lifespan accounting for varying prices of raw materials, product, electricity and both hot and cold utilities. The methanol is synthesized follows the Eq. 1.

$$H_2+CO \longrightarrow CH_3OH \tag{1}$$

The process flow-sheet for production of methanol is presented in Figure 1. Two arrangement of the compressor sequence is included in the flowsheet. Either one compressor with an operating temperature is applied or a sequence of compressor are applied with and additional cooler in-between. In the first approach the operating temperature of the compressor might be out of the optimal operating conditions. In the second approach optimal operating conditions of each compressor can be achieved, however, the investment is increased. The raw material is first compressed and after cooled down to a required temperature. After compressing the raw materials there are two types of reactors with different conversion factor available out of which one is selected during optimisation. After synthesis of methanol a separation should be performed using flash. The liquid outlet of flash contains mainly methanol (content of methanol is selected by user) and vapour consists mainly from unreacted raw material, H_2 and CO_2. Additional stream for reflux is also included in the flowsheet. Compared to the initial process flowsheet presented by Kravanja and Grossmann (1990) the valve after reaction stage has been to change to turbine (ICOMP-reverse compressor, Figure 1) in order to produce electricity. By including the turbine into the system not only the Heat Integration is performed, but also the electricity consumption/ production might be considered. A direct use of shaft-work has been considered instead of converting shaft-work to power and after utilise power for operating compressor. The assumption is reasonable as on the market there are producers offering a combined equipment of turbine on one side connected through shaft with a compressor. In this way besides Heat Integration also the more complex Process Integration can be performed.

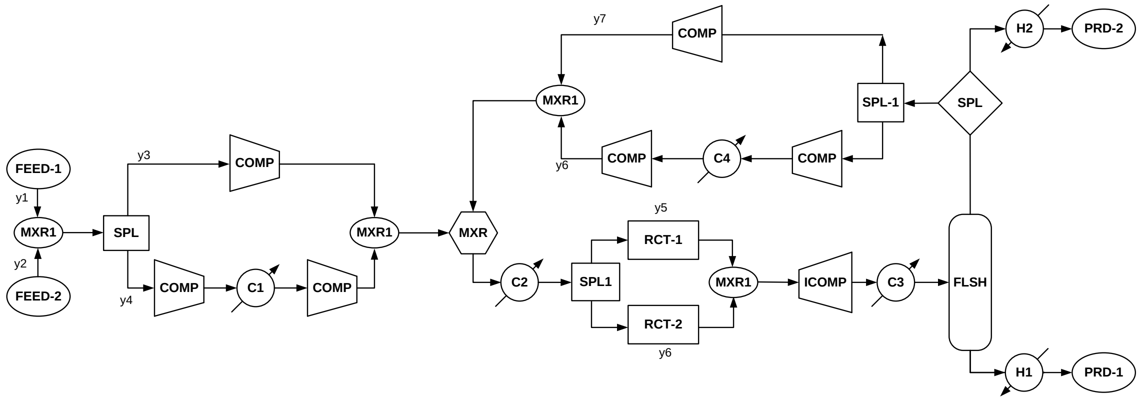

Figure 1: Superstructure of methanol production from H_2 and CO_2 (after Kravanja and Grossmann (1990))

2.2 Price forecast

A price forecast is required in order to achieve an optimal design over whole lifespan, when the economic conditions vary. There are attempts to forecast prices for long term (as long as a lifespan of a process can be) for crude oil prices and also commodities (Kolesnikov, 2013). However, the methodology of obtaining the results of forecast is often not revealed, therefore a relatively simple approach for cost forecast product based on the historical price has been developed. Since the uncertainty of the forecast is high, different scenarios of forecast has been performed for electricity, natural gas cost and methanol price. The feed for methanol production is syngas, which can be produced from many different sources as biomass or coal. However the most common process used is still reforming of natural gas (Coskata, 2013). The price of feed has been determined as the price of hydrogen applying methodology as described Yang and Ogden (2007), where the price of hydrogen is determined according to capital cost required for reforming, capacity of the process, hydrogen yield in the process and prices of natural gas. The historical prices of methanol were taken from Methanex (2013). The electricity prices were taken from Statistical Office of the Republic Slovenia (2013). For the hot and cold utility the connections between energy price, when the fuel used to produce utility has been assumed to be natural gas. The utility prices were determined applying methodology described in Ulrich and Vasudevan (2006) considering forecasted price of natural gas, CEPCI inflation factor, and some technological data as the pressure and the auxiliary boiler steam capacity (kg/s) for process steam and water heat capacity for cooling water (m^3/s).The historical prices for natural gas has been taken from IndexMundi (2013) and the CEPCI inflation factor from Chemical Engineering (2013). After obtaining historical prices the forecast has been made for price in the following way. The middle Projection 2 has been taken as an average of all prices and the function fitted to the point has been used to provide the forecast. The other two projections have been selected by obtaining the average of the points above / below Projection 2. After this step, the procedure is repeated for the price greater/ less than prices of above / below average of Projection 2. The highest prices are included in Projection 1 and the lowest to Projection 3. The probabilities assigned to projections have been 0.5 for Projection 2 and 0.25 for Projection 1 and 3 according to Gaussian distribution. The basis for price forecast for each assumed fluctuation prices is presented in Figure 2.

3. Case Study

The case study has been performed on a process for methanol production. The production of the CH_3OH has been fixed to 1 kmol/s and the temperature of the product has been set to 127 °C. The feed consists from 65 % H_2, 30 % CO and 5 % CH_4. As hot utility steam at 177 °C has been considered, and as cold utility a cold water with inlet 10 °C and outlet 22 °C temperature. Annual working hours are assumed as 8,500 h, tax rate 20 % and interest rate 7 % (including 2 % inflation). The bases for price forecast are the one presented in Figure 2. Fix cost for reactor 1 has been 500 k$, for reactor 2, 650$, and for compressors 50 k$. For heat exchangers the fix prices were 6.5 k$. The variable cost for reactor 1 is 25 k$/y, for reactor 2, 30 k$ and compressor 87.5 $.

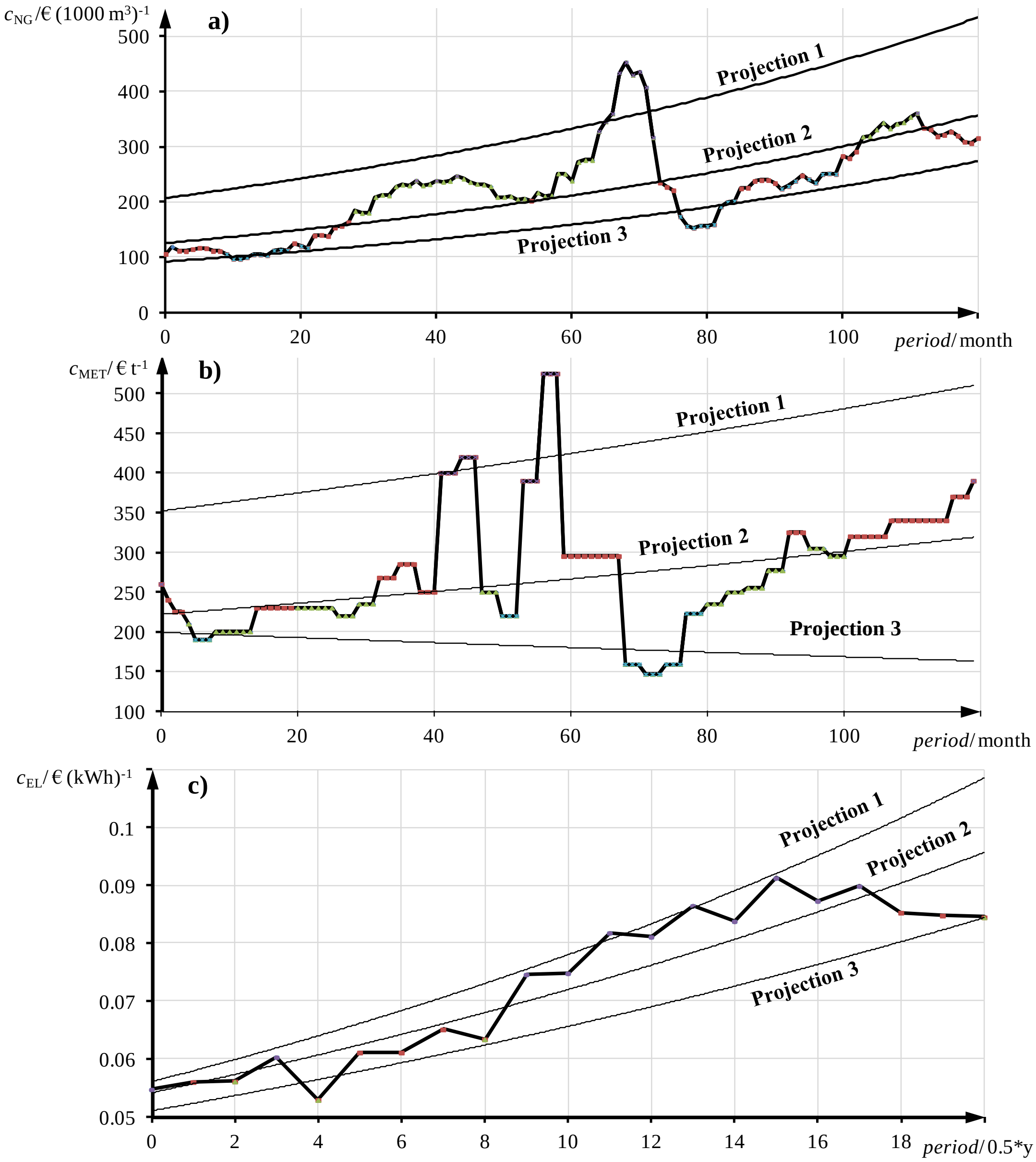

Figure 2: Basis for utility forecast for a) natural gas prices, b) methanol and c) electricity

Table 1 shows the comparison of the synthesis of the process when considering current cost and when considering forecasted cost. As can be seen the design obtained, when assuming forecasted prices economically performed better since the Expected Net Present Value increased by 1.15 %. The Heat Integration resulted in higher heat recovery, decreasing the utility cost.

Table 1: Economic comparison of the design synthesized at current cost and forecasted cost

	ENPV/ M$	*I* / M$	*Q*^{CU}/MW	*Q*^{HU}/ MW	*Q*^{REC}/ MW	W^{EL}/ MW	*V*^{RCT}/ m^3	q^{FEED}/ kmol s^{-1}	q^{REF}/ kmol s-1
Synthesis , considering forecasted cost	686.74	102.65	43.65	0	10.22	51.41	51.27	3.63	11.37
Synthesis, considering current cost	678.96	115.64	53.91	0	9.78	63.34	47.11	3.48	9.81
Difference	7.78	-12.99	-10.260	-	0.44	-11.93	4.16	0.15	1.56
Difference / %	**1.15**	**-24.7**	**-19.03**	**-**	**4.5**	**-18.8**	**8.8**	**4.3**	**15.9**

Also the total investment decreased, despite the increase of the reactor volume. The main savings on the investment occurred at compressor one (COMP-1, Figure 3). The inlet flow of raw materials increased, however, the outlet temperature from compressor one has been significantly reduced. After mixing the raw material and reflux flow the decrease of temperature is reduced, compared to the difference at compressor one outlet temperature. This is a consequence of a higher reflux rate. By higher reflux rate the electricity consumption at compressor two (COMP-2, Figure 3) is increased. However, overall electricity consumption is reduced by 18.8%. The size of reactor increased, due to the higher reflux rate (RCT-2, Figure 3), despite of a slightly reduced conversion of CO to CH_3OH (from 0.3292 to 0.3134). Since the relocation of a heat exchangers (Figure 3) a higher investment in HEN is required, however the heat recovery increased also by 4.5 %.

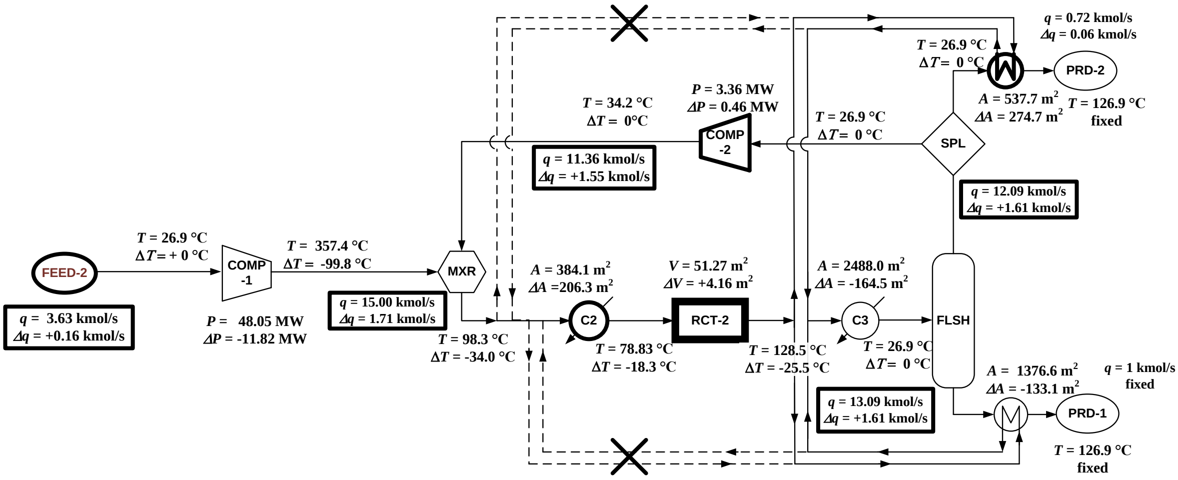

Figure 3: Comparison of the design obtained by optimisation when considering forecasted cost of raw materials, product, utilities and electricity compared with the result of optimisation assuming current cost

The consumption of raw materials increased, despite the cost increase. When evaluating the distribution of cost (Figure 4a) it can be seen, that the highest proportion of the expenditures presents the raw material cost. However, when the potential for saving is determined, the distribution is significantly changed (figure 4b). The potential saving of raw material has been determined as the difference in raw material flow at maximum conversion equilibrium of the key component and the flow obtained during optimisation at current costs multiplied by forecasted cost.

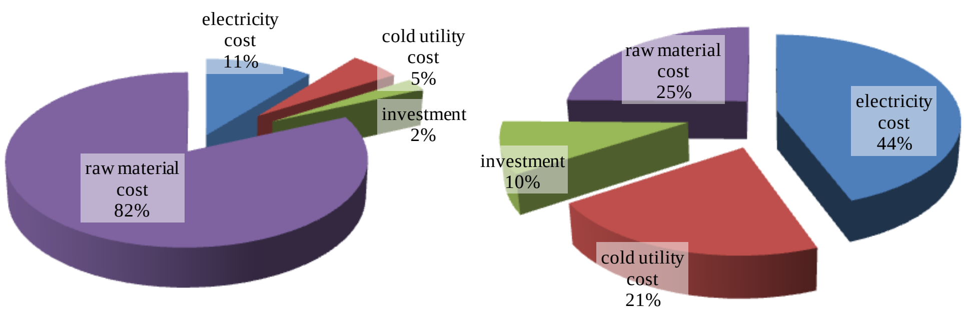

Figure 4: a) Distribution of the expenditures and b) Distribution of potential savings for between raw material, utility, electricity cost and investment

All the other cost has been considered that can be saved 100 %. The comparison has been performed on economical basis. For the expenditure the amount of money spent on a certain cost during entire lifetime after tax determined discounted for present value has been determined. The investment has been assumed to be spent at the beginning of lifetime. The Figure 4b indicates, that the potential saving on raw material is significantly lower, as it seems, when the distribution of expenditure (Figure 4a) is observed.

Therefore, it makes reasonable, why the utility and electricity cost has been decreased, when accounting for forecasted cost.

4. Conclusions

A process synthesis of a methanol production under varying economic conditions has been performed applying a stochastic mixed-integer nonlinear programming (MINLP) model. As can be concluded it is reasonable to apply the model developed, since the design obtained, when considering future utility prices has 1.15 % higher Expected Net Present Value.
Another important inspection is that all the cost variations should be considered simultaneously, as a separate influence might not be determined correctly. As it could be seen by the increase of electricity and utility cost their consumption decreased. However, this is not the case with the raw material consumption. It is increased, despite the cost increase. It has been indicated, that rather a distribution of expenditure a distribution of potential savings of expenditures should be considered, when evaluating the impact of future cost variations.

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