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Sustainable Carbon–Hydrogen–Oxygen symbiosis networks: Intensifying separation sections

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ABSTRACT

The Carbon–Hydrogen–Oxygen symbiosis networks (CHOSYNs) belong to the latest trend of sustainable process design whose main purpose is the efficient use of energy and mass resources. Processes Intensification methodologies have been used to enhance the sustainability of several chemical processes; therefore, this work proposes to involve intensified processes in the synthesis of CHOSYNs to improve the sustainability of the network beyond the integration benefits. The main objective of this work is to evaluate the impact of incorporating intensified processes on the CHOSYN economic, environmental and safety performances. Due to the intensive energy use and low thermal efficiency in distillation sequences, the intensification is focused on these separation processes to improve energy efficiency and reduce operating costs. As a case study is proposed a CHOSYN with conventional processes; thermally couple equivalent configurations are obtained and optimized for suitable distillation sequences of the participant plants, then these sequences are integrated substituting the conventional ones in the final configuration of the CHOSYN. For the conventional and intensified solutions, the variable and fixed costs are determined, the eco-indicator 99 is used to evaluate the environmental aspect, and the safety of the process is assessed by the individual risk.

1. Introduction

The ongoing environmental problems, resource scarcities and the adverse global economic situation are the main drives to planning and developing more sustainable processing systems. This way, cleaner, cheaper and safer processes have been effectively developed through different strategies of process integration and intensification. In this context, the Carbon–Hydrogen–Oxygen symbiosis networks (CHOSYNs) are proposed [1], they are defined as a set of plants that deal mainly with carbon, hydrogen and oxygen compounds, the plants are oriented to share mass and energy resources with other plants through central shared facilities called interception networks. The interception network is made up of different processing units to enable the exchange, conversion, separation, treatment, splitting, mixing and allocation of the shared streams. The main advantage of these networks is the chemical conversion of wastes, by-products or products from one plant to needed compounds in other plants, in this way, it is possible to reduce wastes and raw materials by maximizing the recycling capability reducing the overall need for fresh resources, dischargeable streams and heat requirements, which improve the overall sustainability of the system. The design and configuration of CHOSYNs have been addressed through different approaches and guided by different sustainability aspects, particularly profitability [2] and efficient resource utilization; in this sense, the first works focused on mass conservation using algebraic methods [3], mathematical programming [4], including limited resources [5] and involving water concerns [6], then the mass and heat simultaneous integration were considered [7]. Other sustainable criteria were proposed for an upgraded outcome, which include multicriteria optimization involving economic, sustainability and safety issues [8], the i-safe index was also incorporated [9], and CO_2 footprint restrictions on the network were considered through life-cycle analysis [10].

The previously reported approaches for the synthesis of the CHOSYNs are all based on the proper integration of the resources among the set of plants where the main purpose was to determine the integrated configuration of the CHOSYN: new processing units and new plants and the total allocation of the exchangeable streams. This integration was

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determined by different objective functions considering economic, environmental and safety objectives. Through all these previously reported methodologies, it is possible to reach optimal solutions for the integration of resources, which, in theory, under the respective objective function are also the ones with the best features of sustainability, however, this is only concerned with the integration of plants and resources whose benefits are undeniable.

When a CHOSYN is designed, besides the plants that already exist, other plants are proposed to install; in this context, many necessary separation processes are involved in the network. This is very important to notice that while integration mitigates some negative aspects of the sustainability, other negative aspects arise precisely due to the nature of the new integration and a large number of involved plants, and these are presented through the inherent inefficiencies of the separation processes, in particular for distillation operations. For some decades now, process intensification (PI) has gained attention in the task of improving the efficiency of processing systems, and the particular case of the intensification of distillation sequences has been extensively studied.

Process intensification has demonstrated the potential to significantly improve process efficiency and safety while reducing cost [11], which applies to both existing and conceptual processes [12], Keil presented a review about how PI aims at safer and sustainable technological developments [13], moreover, PI derives from the necessity of substantially improving the performance of process plants [14], and strives for innovative equipment and process configurations to overcome existing limitations [15], furthermore, several authors agreed that PI strategies are broader than process integration [16], it represents the limit case of tight integration through significant material recycling [17], and they play a major role in achieving the desired improvements in process synthesis [18].

For all the above mentioned, this work proposes a new point of view considering process separations as opportunities to improve the network and process intensification techniques as the tool to achieve this improvement. It is proposed a strategy to involve process intensification methodologies to intensify the distillation sequences generated when a CHOSYN is designed. In this way, the inefficiencies of the distillation sequences that contribute negatively to the sustainability of the CHOSYN network can be mitigated, thus improving the sustainability objectives, in this work it is proposed to evaluate three important aspects of sustainability: economic, environmental and safety. To demonstrate whether the proposed strategy is actually improving the sustainability objectives, it is proposed a case study of a CHOSYN with conventional distillation sequences that are intensified, then the sustainability objectives of the two solutions will be evaluated. To the best of our knowledge, this work is the first one that incorporates intensified processes in CHOSYNs.

2. Intensification sites

According to PI definitions, it can be highlighted the integration and coupling of operations, phenomena and functions into an enhanced operation. Tian et al. [19] provided an overview of PI technologies under four categories: advanced separation, advanced reaction, combined reaction/separation, and alternative energy sources. This work focuses the efforts on improving the separation processes that can account for a large fraction of the total capital and operating costs [20], which typically account for about 60 to 80% of the process cost in most mature chemical processes [21] and 40 to 60% of the energy requirements of the process [22]. Particularly, this work is focused on distillation operation units, which are the most used separation process and one of the most energy and capital-intensive technologies [23]. The main driver of process intensification in distillation sequences is pursuing energy efficiency, but in addition, intensified alternatives present important capital savings [24]. Thus, intensifying the distillation sequences included in the CHOSYNs can improve the sustainable targeted criteria of the overall network. The next sections describe the considered intensified separation processes.

2.1. Thermally coupled distillation

Conventional distillation sequences have inherent inefficiencies produced by the thermodynamic irreversibility due to the well-known remixing effect of streams at the feed, top and bottom of the columns [25]. The search for avoiding these inefficiencies leads to thermally coupled distillation sequences (TCDS) designed for multicomponent distillation systems, which can reduce energy consumption by up to 30% compared with conventional configurations [26], arrangements such as Petlyuk column can achieve energy savings of up to 50% [27], also improvements of thermodynamic performance yield TAC savings [28]. Ramírez-Corona et al. [29] summarized the most studied types of thermally coupled arrangements: systems with side columns (side rectifier and side stripper), the fully thermally coupled system (Petlyuk column); and their simplified alternatives by reducing vapor-liquid interconnections. Caballero [25] highlighted the importance of dealing only with thermodynamically different alternatives because differences between thermodynamically equivalent alternatives are only important at the operational level.

The optimal arrangement is usually located between fully thermally coupled sequences and the conventional configuration, and the enhancement achieved by these intensified alternatives relies on the feed conditions and composition.

3. Sustainable targeted criteria considered for CHOSYNs performance

Several metrics have been used to measure the level of sustainability in chemical processes, this sustainability is not only based on waste and emissions generation but on many other aspects like resource usage efficiency, environment preservation, health and safety.

Despite the many definitions of the term sustainability, it is possible to identify some basic requirements that need to be satisfied before making claims about sustainability. In particular, Jiménez-Gonzalez [30] proposed clear mathematical strategies to evaluate those sustainability metrics. In this sense, sustainability can be viewed as a framework with targets to achieve economic, environmental, inherent safety indexes, among others. According to Curzons et al. [31], the cost assessment, the life cycle impact assessment and risk minimization are within this framework of sustainable development. This work addressed the sustainability evaluation of the CHOSYNs through costs (capital and operating), environmental impact (Eco-indicator 99) and safety (risk index), which impact directly the economic, environmental and social aspects, respectively, and so in the sustainable design for the CHOSYNs.

3.1. Economic criteria

The economic evaluation of resulting configurations is addressed by the total annual cost of the CHOSYN, this involves the annualized investment cost over the payback period, which includes equipment and installation cost, and the operating costs (see Eq. (1)):

$$TAC = \left(\frac{Total\ Capital\ Cost}{Payback\ Period}\right) + Operating\ cost \tag{1}$$

The operating costs include the cost of raw materials and the utility costs, in the case of the present work the IP does not affect the amount of raw material needed, so for the cost analysis, the operating costs are equivalent to the utility costs. The utilities needed are calculated by the software Aspen Plus and the payback period is of 10 years.

3.2. Energy efficiency

The thermally coupled distillation sequences are more energy-

Table 1
Impact categories used for the EI99 evaluation [33].

Impact category	Steel (points/kg) (× 10^{-3})	Steam (points/kg)	Electricity (points/kWh)
Carcinogenic	1.29×10^{-3}	1.180×10^{-4}	4.360×10^{-4}
Climate change	1.31×10^{-2}	1.27×10^{-3}	4.07×10^{-3}
Ionizing radiation	4.510×10^{-4}	1.91×10^{-6}	8.94×10^{-5}
Ozone depletion	4.550×10^{-6}	7.78×10^{-7}	5.41×10^{-7}
Respiratory effects	8.010×10^{-2}	1.56×10^{-3}	1.01×10^{-5}
Acidification	2.710×10^{-3}	1.21×10^{-4}	9.88×10^{-4}
Eco toxicity	7.450×10^{-2}	2.85×10^{-4}	2.14×10^{-4}
Land occupation	3.730×10^{-3}	8.60×10^{-5}	4.64×10^{-4}
Fossil fuels	5.930×10^{-2}	1.24×10^{-2}	1.01×10^{-2}
Mineral extraction	7.420×10^{-2}	8.87×10^{-6}	5.85×10^{-5}

efficient and present a lower heat duty than the conventional sequences for the same separation, this saving is determined by the percentage ratio given in equation 2:

$$\text{EnerrySavings} = \left(1 - \frac{Q^{\text{intensified}}}{Q^{\text{convetional}}}\right) \times 100 \quad (2)$$

3.3. Environment impact

The environmental aspect is evaluated through the Eco-Indicator 99 (see Eq. (3)). This methodology is based on the life cycle analysis, where different damage categories of a production process are weighted, these categories are human health, ecosystem quality and resources, minerals and fossil fuels [32,33]. After weighting each category, a score is calculated for the overall process represented on a point scale with normalized results which enables objective comparison among a set of process options. The EI-99 can be mathematically expressed by Eq. (3), where w is the weighting factor for damage, c_i is the value of the impact category i, and α_j is the value of the impact subcategory j.

$$EI99 = \sum_i \sum_j w c_i a_j \quad (3)$$

The evaluated most important subcategories are the steel necessary for the equipment, electricity for pumping and compressing, and the steam needed for heating, the values for these impact categories are shown in Table 1.

3.4. Inherent safety

The risk assessment is carried out through the Individual Risk Index, it belongs to the quantitative risk approaches and it is defined as the risk of injury or decease to a person in the vicinity of a hazard. It is determined by the frequency of incidents and the probability of injury or decease caused by these incidents and it is mathematically defined by Eq. (4), where f_i is the frequency that the accident i occurs and $P_{x,y}$ is the probability of injury or decease caused by the same accident.

$$IR = \sum f_i Px, y \quad (4)$$

In this work, the considered accidents for the risk analysis are jet fire, flash fire and toxic release for continuous release accidents, and boiling liquid expanding vapor explosion BLEVE), unconfined vapor cloud explosion (UVCE), flash fire and toxic release for instantaneous release accidents. The occurrence frequency of the accidents [34,35] is shown in Fig. 1, in the supplementary material it is detailed how the probability terms were computed.

4. Proposed approach

The main aim of this work is to present a strategy to approach the sustainability of the separation processes for the different plants that constitute the CHOSYN through the implementation of intensified processes. More concretely, in this work, conventional distillation sequences used in the different plants of the CHOSYNs, which are suitable for intensification, are replaced by thermally coupled distillation sequences that offer a better sustainability performance. The goal is to strengthen the general sustainability of the CHOSYN through these design changes.

Fig. 2 shows the flowchart of the proposed approach, the sequential method is proposed to avoid the simultaneous design of the CHOSYN, the thermally coupled sequences and their optimization. The first step is the synthesis of the CHOSYN with conventional flowsheets of the plants using a reported approach (e.g. mathematical programming, simulation, etc.). In this case, it is used a simulation approach that is more convenient because the next step is the rigorous simulation of the synthetized network, in this work is used the software Aspen Plus for this task.

The next task is to identify which distillation sequences can be

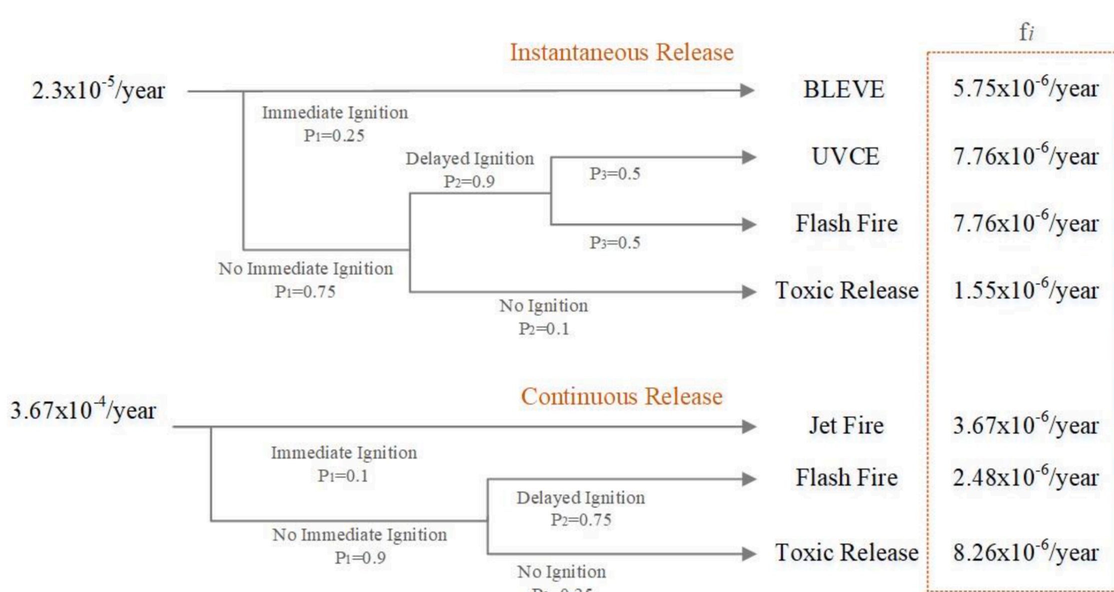


Fig. 1. Event tree for instantaneous and continuous incidents [35].

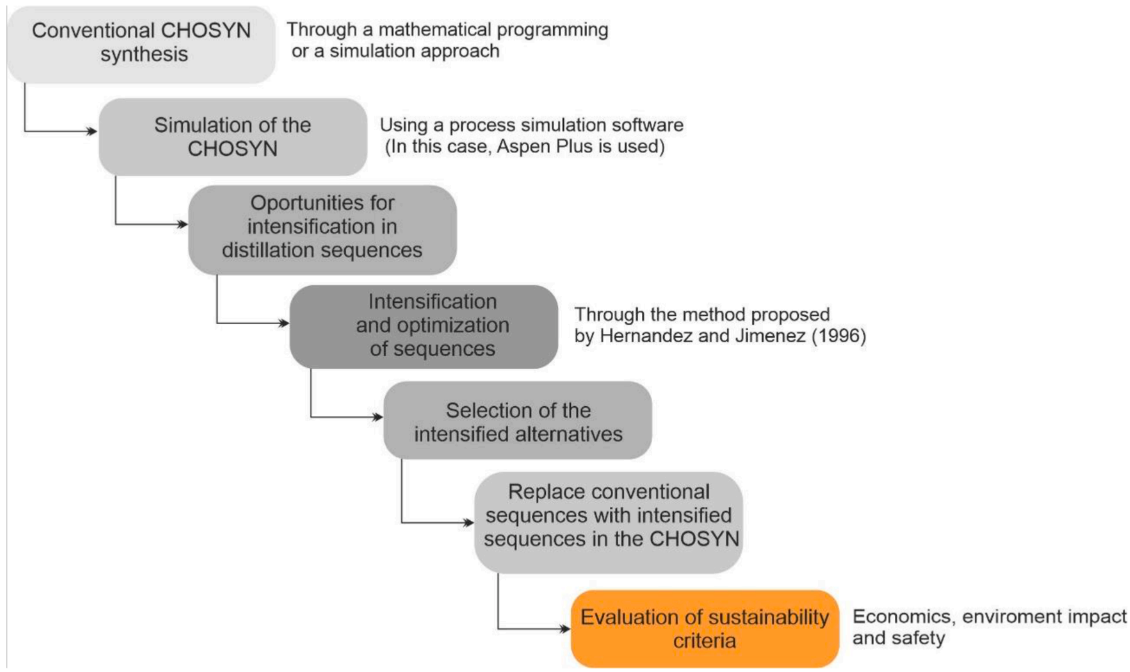


Fig. 2. Flowchart of the proposed approach.

Table 2
Considered configuration for the case study.

Plant	Description	Processing capacity (ton/day)				Distillation columns
		S1	S2	S3	S4	
P1	ATR (auto thermal reforming of natural gas)	13400	13400	13400	13400	-
P2	Ethylene production from ethane cracking	110	110	110	110	Three columns sequence: C-201 (demethanizer) C-202 (depropanizer) C-203 (de-ethanizer)
P3	Propane dehydrogenation to propylene	2200	2200	2200	2200	C-301 propylene purification
P4	Methanol to propylene	300	300	300	300	Two column sequence: C-401 (debuthanizer) C-402 (propylene purification)
P5	Vinyl acetate monomer process	150	150	150	150	C-501 (acetic acid separation)
P6	Methanol production from syngas	1110	680	882	680	C-601 (methanol dehydratation)
P7	Methanol production from CO_2/H_2	1872	2270	2152	2340	C-701 (methanol purification)
P8	Steam methane reforming to syngas	-	-	253	-	-
P9	Steam methane reforming to CO_2	-	37.5	-	-	-
P10	Dry Reforming of methane	382	-	-	382	-
P11	Water gas shift reaction	-	-	-	25	-
P12	Carbonylation of methanol to Acetic acid	202	202	202	202	C-1201 (acetic acid purification)

intensified, then the thermally coupled sequences are proposed and optimized for these sequences. In this work, in particular, from the set of alternatives, there are selected the most thermally efficient and those with the lowest cost. Then, these alternatives replace the conventional sequences on the CHOSYN configuration, the sustainability criteria proposed are evaluated for the conventional configuration and for the intensified alternative to show the boost over these criteria by the intensification.

4.1. Case study

A case study is presented to show how to apply the proposed approach, this case study has been previously reported in different research works. Juarez-Garcia et al. [36] presented a systematic approach using simulation software for rigorous CHOSYN synthesis, through this approach and with the objective of the maximum use of the available resources, they presented four different configurations for the same CHOSYN, these configurations consisted of schemes of eight and nine plants, with different processing capacities and stream allocation throughout the network. This work resumes these configurations for the present case study, analyzes the opportunities for intensification and includes the best-intensified option in each previous solution to obtain new intensified alternatives with the best energy usage performance. Table 2 summarizes the four solutions and indicates the distillation columns used in each process plant according to their respective process flowsheets.

For the four solutions, there are two opportunities for implementing thermally coupled alternatives to the conventional sequences: in Ethylene and MTP processes (see Fig. 3). Through the intensification and optimization of these sequences, better values for the sustainability criteria are expected.

4.1.1. Ethylene purification sequence

This sequence consists of three distillation columns (see Fig. 4a), the feed is a mixture rich in ethylene with a mole fraction of 0.69 and methane 0.24, with traces of ethane 0.05, propane 0.01 and propylene

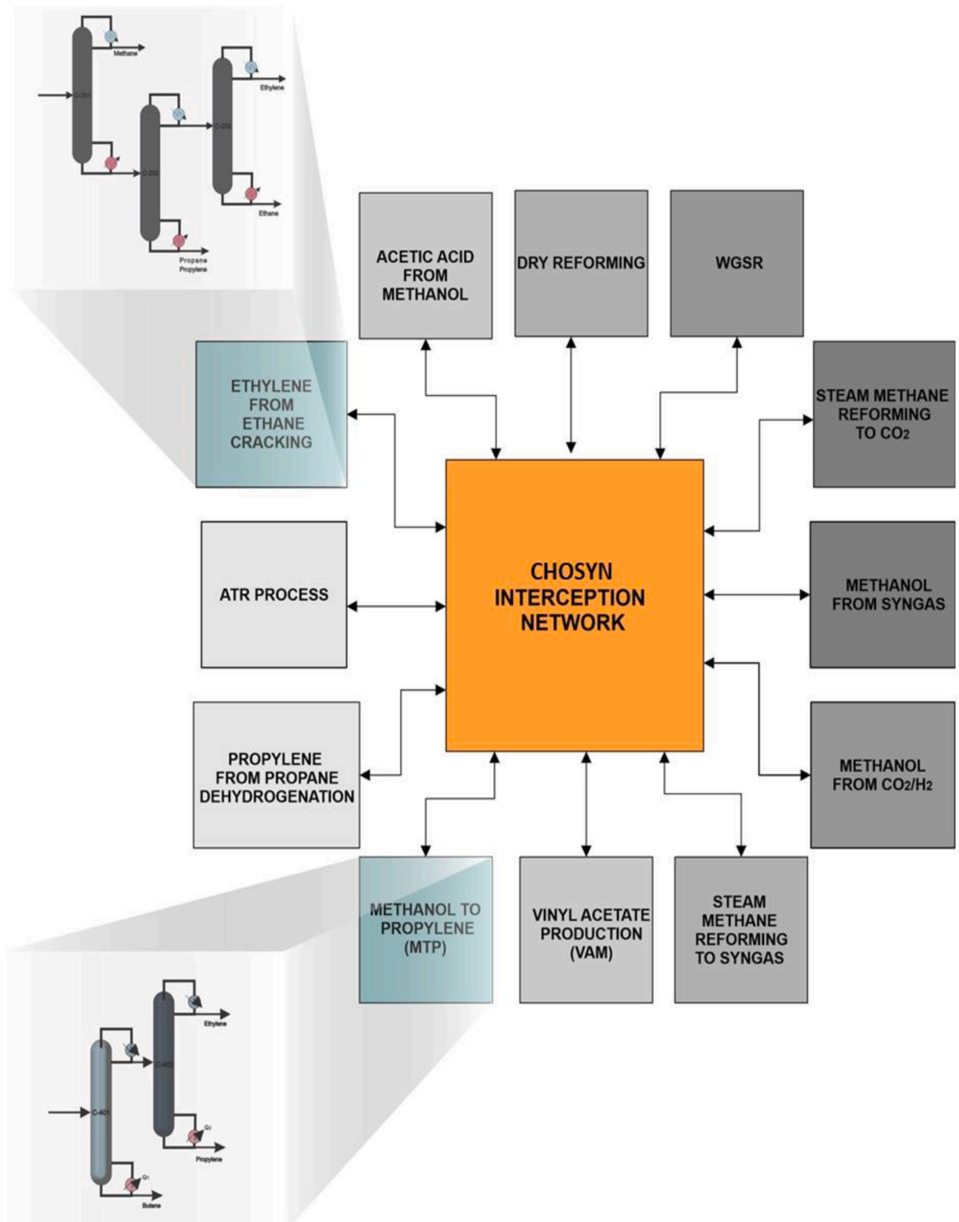


Fig. 3. Opportunities for process intensification in the process separation of the case study.

0.02. In the first column C-201, the methane is separate for the top stage, the second column C-202 removes the propane, propylene and heavier for the bottom, and in the third column C-203 the ethylene is purified to 99.9% in the light stream.

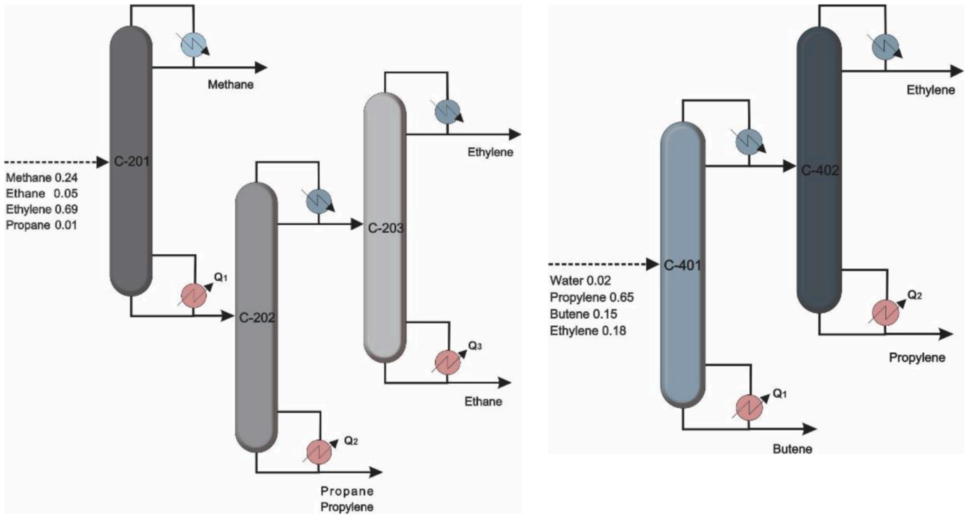
4.1.2. *Propylene purification sequence*

This is a two columns sequence, the mixture contains traces of water with 0.02 mole fraction, propylene 0.65, ethylene 0.18 and butenes 0.15. The first column C-401 separates the butenes by the bottoms, the second column C-402 purifies the propylene to 99.9% in the heavy stream and ethylene in the light stream (see Fig. 4**b**).

4.2. *Intensification of distillation sequences*

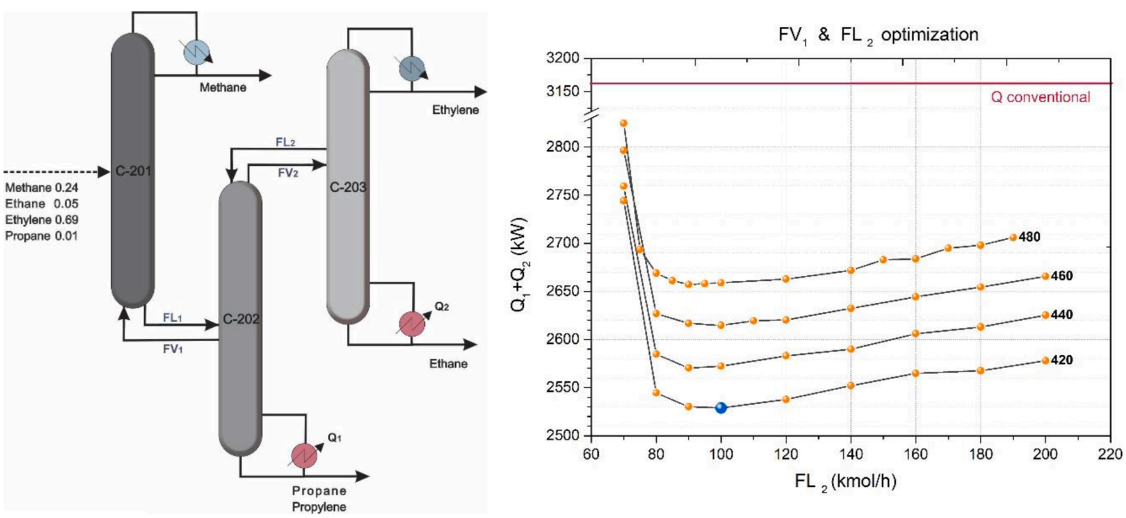
The thermally coupling sequences to replace the conventional sequences with a lower energy consumption were obtained using the dynamic method proposed by Jimenez and Hernandez [37]. For each sequence, first, there are found preliminary schemes of the thermally coupled sequences for later being rigorously simulated using Aspen Plus, where the interconnection flows are also optimized for the minimum heat duty of the system. The resulting intensified sequence for ethylene purification is shown in Fig. 5**a**; there are three possibilities for coupling the columns: replacing the reboiler of C-201 for a vapor recirculation, replacing the condenser of C-202 for a liquid recirculation, and replacing both, the energy savings are 14.6%, 11.1% and 20% respectively over the conventional sequences for the optimum recycle stream. For the present analysis, the double recycle option is addressed due to the saving percentage. The optimization for the selected sequence is shown in Fig. 5**b**, the red line represents the heat duty of the conventional option, and the blue point the optimum vapor and liquid recycled flow.

For the two columns for the propylene purification system, two options are analyzed: the Petlyuk column with an energy saving of 14.4% and the indirect sequence of the column with a side stripper whose energy-saving is 17.5%, according to these results the indirect sequences is selected for the present analysis. Fig. 6**a** shows the intensified scheme and Fig. 6**b** the optimization of the liquid recycled flow (blue point)



a) Ethylene purification b) Propylene purification

Fig. 4. Distillation sequences suitable for Intensification.



a **b**

Fig. 5. a. Thermally coupled sequence for ethylene purification. Fig. 5b. Vapor and liquid recycled flow optimization for the minimum heat duty.

compared with the heat duty of the conventional option (red line).

Table 3 shows the topology of both intensified and conventional selected designs for the present analysis for ethylene and propylene purification. According to the reflux ratio and the number of stages, the ethylene sequence does not vary significantly from the conventional design; whilst in the sequence for the MTP process, the column C-401 intensified should be noticeably larger than the conventional design. Table 4 shows a summary of the interconnection flows.

4.3. Coupling intensified processes to the CHOSYN

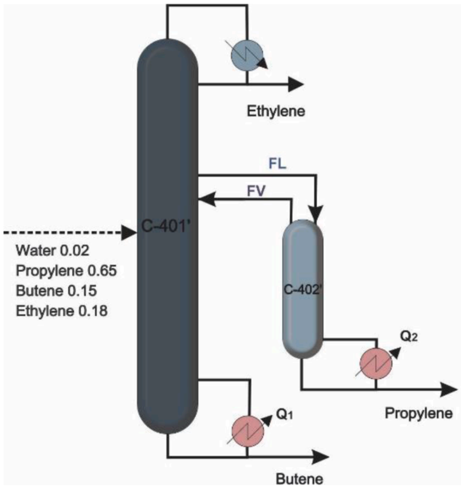
Once the intensified options to replace conventional processes have been obtained and selected, the coupling of Conventional CHOSYN/intensified processes is accomplished using Aspen plus for the four solutions of the case study, in this way four pairs of solutions are obtained, then the evaluation of the proposed sustainability criteria is carried out to each pair of solutions and compared only with their homologous (conventional vs intensified) to perform an objective comparison and determine the real enhancement or decrement over these criteria by the involving of intensified processes.

5. Results and discussion

This section presents the analysis of the results obtained from the evaluation of the three sustainability criteria considered. The case study contemplates four different solutions for the configuration of the same network, the following results are shown for each of the solutions (S1-S4) conventional "C" and intensified "I".

5.1. Economic evaluation

Through the economic analyzer available on the Aspen Plus software, there are obtained the parameters to determine the different expenses associated with the CHOSYN, as in this case, the intensification does not affect the allocation and the amount of mass resources needed, the costs associated with these resources are equivalent for the conventional and the intensified solutions. In the case of the ethylene sequence, the intensification enables to dispense with a condenser and a



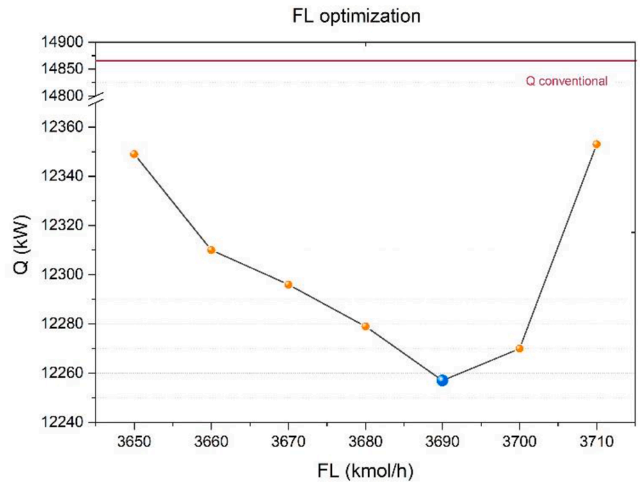


Fig. 6. a. Thermally coupled sequence for propylene purification. Fig. 6b. Liquid recycled flow optimization for the minimum heat duty.

Table 3
Design specification for the intensified columns.

		C-201	C-202	C-203	C-401	C-402
Stages	Intensified	26	42	86	68	15
	Conventional	26	42	86	50	33
Feed stage	Intensified	8	20 liquid from C-201′ 1 liquid from C-203′	47	44 19 vapor from C-402′	1 liquid from C-401′
	Conventional	8	20	47	26	18
Condenser	Intensified	partial	none	none	partial	none
	Conventional	partial	partial	partial	partial	partial
Reboiler	Intensified	none	kettle	kettle	kettle	kettle
	Conventional	kettle	kettle	kettle	kettle	kettle
Reflux ratio	Intensified	6.5	0.356	5	23.6	1.66
	Conventional	9.47	0.45	4.05	2.45	11.3
Reboiler duty (kW)	Intensified	0	1523.9	1005	6028	6257
	Conventional	1159.6	570.1	1433.02	9169.7	5694.5
Pressure (bar)	Intensified	28	28	28	28.5	28.5
	Conventional	28	28	28	28.5	28.5
Distillate rate (kmol/hr)	Intensified	58.54	–	168.4	403	–
	Conventional	58.54	179.2	168.3	1857.5	401.9
Bottoms rate	Intensified	–	6.4	4724.4	351.1	1478.4
	Conventional	185.69	6.4	10.87	375	1455.5

Table 4
Description of the interconnection flows of the intensified solutions.

	Ethylene sequence				Propylene sequence	
	FV_1	Fl_1	FV_2	FL_2	FV	FL
kmol/hr	605.7	420	279.3	100	2211.5	3690
From	stage 21 of C-202	Stage 26 of C-201	Stage 1 of C-202	Stage 46 of C-203	Stage 1 of C-402	Stage 18 of C-401
To	stage 26 of C-201	Stage 20 of C-202	Stage 47 of C-203	Stage 2 of C-202	Stage 19 of C-401	Stage 1 of C-402

reboiler which reduce the equipment cost and the utility cost (lower heating and cooling requirements). For the case of MTP intensified sequence, the utility cost is also reduced by the dismissal of the condenser of the second column, but in this case the number of stages of the first column increases and therefore the size of the column, and consequently the equipment cost increases. For the four solutions, the lower equipment cost of the ethylene sequence does not make up for the equipment cost of the intensified MTP sequences, however, this cost is fixed and the difference with the conventional arrangement is not so appreciable (see Fig. 7)

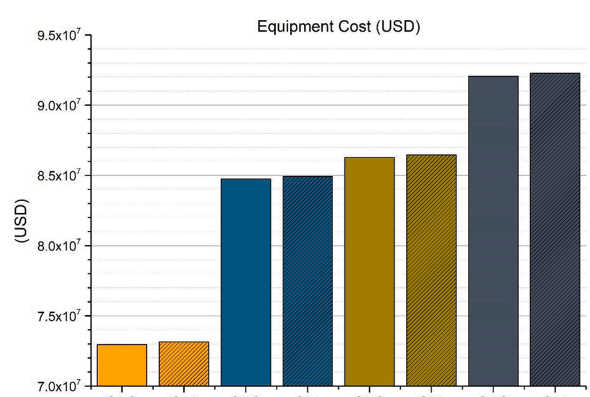


Fig. 7. Equipment costs for intensified and conventional configurations.

On the other hand, the utility costs for the four intensified solutions

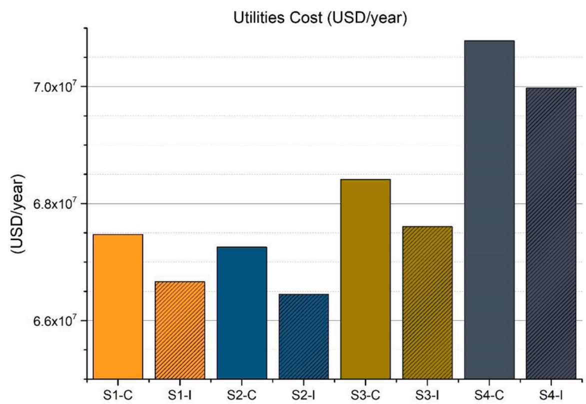


Fig. 8. Utility costs for intensified and conventional configurations.

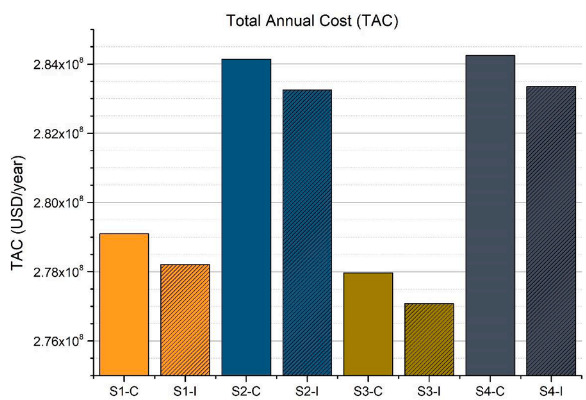


Fig. 9. Total annual cost of the intensified and conventional CHOSYN.

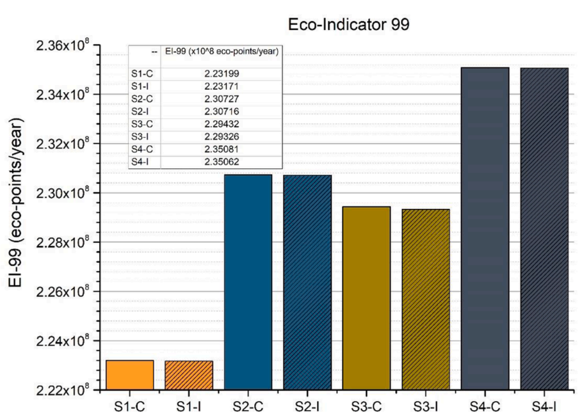


Fig. 10. Eco-indicator 99 for the intensified and conventional CHOSYNs.

are lower than the conventional options (see Fig. 8) due to the higher thermal efficiency achieved through the intensification: less heating and cooling requirements. The Total Annual Cost (TAC) is strongly dependent on the variable costs, as was mentioned the costs associated with raw materials (mass resources) are equivalent for the intensified solution and the conventional arrangement, the decrease in the TAC is shown in Fig. 9, which is entirely due to the intensification involved.

The cost factor that produces the highest percentage of improvement in the TAC is the operating cost which is directly related to the cost of heating in the column reboilers that would be expected for any case study and different alternatives of thermally coupled distillation sequences. Unlike in the case of equipment cost, which has a smaller contribution to the TAC improvement, and although in this as in other

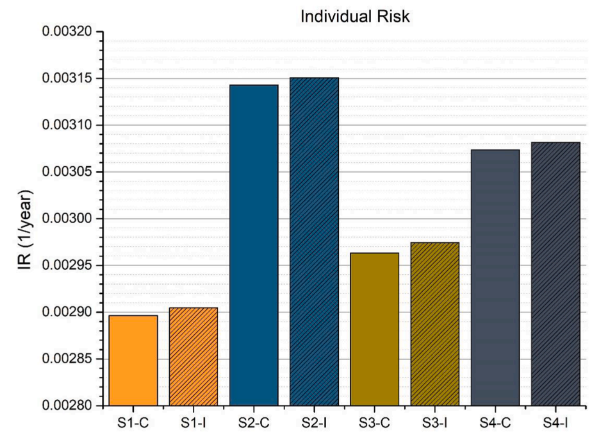


Fig. 11. Individual risk for the intensified and conventional CHOSYNs.

cases due to the intensification, larger equipment size and cost might be required, this would not produce an effect that would offset the TAC gain due to operating cost savings.

5.2. Environmental evaluation

The results for the Eco-Indicator 99 are shown in Fig. 10. The magnitude of the EI99 value for the overall CHOSYN system is due to the number of selected plants and their processing capacity, for each solution there is a large number of operating units and equipment involved in the networks (146 for the solution with less equipment): reactors, heat exchangers, pumps, compressors, flash separators, and absorption and distillations columns were taken into account for the present evaluation. However, this evaluation does not say if the process is environmentally friendly but if the intensified solutions of the CHOSYN produce less affectation on the environment. The categories of impact selected to evaluate the EI-99 are directly affected by the intensification, despite the thermally coupled columns present a bigger diameter in both intensified sequences, all intensified alternatives present better values for the EI-99, as mentioned above, the reduction of the heat duty due to the replacement of reboilers and condensers reduces the affectation on the subcategories of impact: less steel is required to the construction of equipment, steam is reduced and also the electricity required in the intensified columns. Overall, this leads to an improvement in sustainability compared to conventional configurations. Even if the improvement of the environmental impact is not so significant in this case study, it is undeniable and follows the same direction as the economic benefit, and this can also be extrapolated to other case studies that, according to their topology, this impact would be more noticeable.

5.3. Safety evaluation

In the case of risk assessment, the behavior of the results is the opposite of the two previous ones. Fig. 11 shows the individual risk results for the different configurations, the causative variables related to the process which causes injuries or death for the different accidents considered are the operating conditions and the stock and concentration. In this case, the pressure is barely affected by intensification, the temperature profile variations through the coupled columns are more noticeable on the MTP sequences in the first column (C-401′), and less important in the ethylene sequence. The reflux ratio drops in columns C-201, C-202 and C-402, this reduces the internal flows that allow smaller tower diameters, which consequently reduces the risk associated. In the opposite case, for columns C-203 and C-401, the internal flows increase along with the reflux ratio, this variation is more important for C-401, which is then responsible for the increased individual risk of the network since the decrease in the risk of the smaller columns does not compensate the risk of this column.

However, although for this case study the CHOSYN risk indicator is negative, it cannot be generalized to other case studies, and the results depend more on the shape of the function for risk as a function of increasing equipment size due to intensification and the physical and chemical properties of the components of the mixture to be separated in the sequence.

6. Conclusions

Previously reported approaches for designing CHOSYNs had focused on the optimal integration of the different plants and resources in the network; however, it should be noticed that during this integration several separation processes are generated and these are the ones that impact the most on the sustainability of the network because they are the most intensive energy processes, especially the distillation operation, which impacts the economic and environmental objectives, and according to their operating conditions these could also impact on safety. Therefore, this work has proposed a strategy to involve process intensification techniques in the CHOSYNs design for addressing the energy inefficiencies produced in distillation sequences that had not been previously considered. A case study has been presented, where the results of the proposed strategy showed that replacing conventional distillation sequences with thermally coupled sequences enables a reduction in energy consumption and exhibited important energy savings of about 20% from their conventional analogous. This higher efficiency was also translated to other sustainability criteria. This work has proposed to evaluate the sustainability of the system through the economic, environmental and safety aspects, so a gain in all or any of the aspects would strictly mean an improvement in sustainability unless one or two of the aspects present a very negative value that counteracts the gain of the other or other aspects. Thus, if sustainability is measured qualitatively as a whole, the decision will be relative to the priorities of the decision-maker, and different weights should be assigned to each of the considered aspects. However, these weights are based on the decision-makers priorities. For the proposed case study, the economic and environmental aspects are benefited from the intensification. First, the economic objective, despite the equipment cost, is slightly higher than the conventional arrangement and the utility cost is noticeably reduced which also decreases the total annual cost. The environmental impact is also reduced by intensification considering the impact of the used equipment and utilities. Particularly for the addressed case study, the results of the risk assessment do not improve with intensification, this is due to the sizing of the columns and the internal flows; however, this impact is not significant concerning the economic and environmental objectives. Therefore, it can be established that for an optimal design of a CHOSYN, where the sustainability objectives have been achieved through the integration of resources, IP techniques enable to further improve these objectives by tackling the inefficiencies of the distillation sequences that are generated during the designing of the network.

CRediT authorship contribution statement

Maricruz Juárez-García: Conceptualization, Software, Writing – original draft, Methodology, Data curation. **Gabriel Contreras-Zarazúa:** Software, Validation, Methodology. **Juan Gabriel Segovia-Hernández:** Conceptualization, Methodology, Writing – review & editing. **José María Ponce-Ortega:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cep.2022.109092.

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