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Capital cost estimation of CO_2 capture plant using Enhanced Detailed Factor (EDF) method: Installation factors and plant construction characteristic factors

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ABSTRACT

Capital cost is frequently estimated for new and retrofit carbon capture plants as new concepts for cost reduction emerge. Capital cost during initial cost estimation of chemical plants strongly depends on the installation factor (s) of the methodology employed. How these installation factors respond to the cost of each equipment determines the total plant cost and the type of capital cost (new plant or modification project) each method is suited for. The effect of equipment installation factors on capital cost of an amine-based CO_2 capture plant using the Enhanced Detailed Factor (EDF) method has been studied. Plant construction characteristic factors have also been introduced to account for different plant construction characteristic situations. The impacts of the installation factors of seven methodologies on capital cost were compared. A uniform installation factor will likely lead to overestimation of very expensive equipment and underestimation of less expensive equipment. EDF method's installation factors respond based on each equipment cost. Even though all the methods estimated the optimum ΔT_{min} in the cross-exchanger to be 15°C, the cost estimated was €66/tCO_2 by the EDF method, Smith's percentage of delivered-equipment factorial method and Hand's factorial method; and €69–79/tCO_2 by the other methods. The results demonstrate that the EDF method is suitable for estimating capital cost for new plants and modification projects, small and large plants, and accounts for different plants' situations.

1. Introduction

The amine-based CO_2 absorption and desorption process is the most mature technology for carbon capture to mitigate global warming (Rubin et al., 2015). It can be built together with a new process plant or as a retrofit to an existing process plant. Nevertheless, the cost of deploying this technology at an industrial scale is currently high.

Cost engineering and economics play a crucial role in assessment of carbon capture technologies (van der Spek et al., 2019). Cost is the key decisive factor when considering industrial deployment of a technology when a choice among many options is to be made (Ali et al., 2019). Estimates of carbon capture and storage processes are vital for making policies, and for making important decisions like funding of research and project, as well as investment in industrial implementation (Rubin et al., 2013).

Greater cost savings in CO_2 capture and storage processes could be realised when a full-scale CO_2 capture plant has been built and put in operation, and an entire value-chain from capture to storage will have been established (Sprenger, 2019). The Norwegian government is set for construction of a plant to capture CO_2 emitted from Norcem cement plant at Brevik in Telemark, Norway (Thorsen, 2020). And it has been emphasized that as work goes towards construction of a full-scale industrial CO_2 capture plant, research will continue to play a central role (Sprenger, 2019). Cost estimation will play an important role in assessment and establishment or transfer of the experience and gains in capital and operating costs from the first set of capture plants (First of a kind-FOAK), to build more cost-efficient plants in the future (Nth of a Kind-NOAK). The learning curve may be steep due to all the studies and progress already made.

The Director of NTNU Energy, Johan Einar Hustad has emphasised that carbon capture and storage (CCS) must become a subject at the universities, to ensure successful application of CCS technology at industrial scale (Sprenger, 2019). This means, cost estimation activities will increase not just in the process industry but also in the universities and other research institutions. Carbon capture cost estimates for the

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Nomenclature

BEC [€]	Bare Erected Cost
CAPEX [€]	Capital expenditure
CCS	carbon capture and storage
$C_{Eq.,CS}$ [€]	Equipment cost in CS
$C_{Eq.,other\ mat.}$ [€]	Equipment cost in other material, e.g. SS
CS	Carbon steel
DCC	Direct Contact Cooler
ΔT_{min} [°C]	Minimum approach temperature of heat exchanger
EDF	Enhanced Detailed Factor
EIC	Equipment Installed Cost
EPCC	Engineering, Procurement and Construction Cost
$f_{administration}$	Sub-installation factor for administration costs
$f_{commissioning}$	Sub-installation factor for commissioning costs
$f_{contingency}$	Sub-installation factor for contingency costs
f_{direct}	Sub-installation factor for direct costs
$f_{EIC,CS}$	Equipment installed cost in CS
$f_{EIC,other\ mat.}$	Equipment installed cost in other materials, e.g., SS316
$f_{engineering}$	Sub-installation factor for engineering costs
$f_{Eq.}$	Sub-installation factor for equipment, it is equal to 1
f_M	Material factor
FOAK	First-of-a-kind
f_{pp}	Sub-installation factor for piping costs
$f_{pp,CS}$	Sub-installation factor for piping costs in CS
$F_{T,CS}$	Total installation factor for equipment constructed in carbon steel
$F_{T,other\ mat.}$	Total installation factor for equipment constructed in other materials
k€	x 1000 Euro (x1000€)
kNOK	x 1000 Norwegian Kroner
MEA	Monoethanolamine
n	Plant operational lifetime
NOAK	Nth-of-a-kind
NOK	Norwegian Kroner
O&M	Operational and Maintenance
OPEX	Operational expenditure PCCF
PCCF	Plant construction characteristic factor Interest rate
r	Interest rate
TPC	Total Plant Cost
USD	US dollars

Table 1
Capital cost nomenclature and aggregation method established on BEC (Rubin et al., 2013)

USDOE/NETL (2011)	EPRI (1993)	IEAGHG (2009)	ZEP (2011)	GCCSI (2011)
BEC	BEC	Installed costs		BEC
+	+	+		+
EPCC	EPCC	EPCC	EPCC	EPCC
+	+	+	+	+
Contingencies =	Contingencies =	Contingencies =	Owner's costs (includes contingencies) =	Contingencies =
Total Plant Cost	Total Plant Cost	Total Plant Cost		Total Plant Cost[a]
+				
Owner's costs =				
Total Overnight Cost			Total Investment Cost	Total Overnight Cost[a]
				+
				Owner's costs
+	+	+		+
IDC	AFUDC	IDC		IDC =
+	+			
Escalation =	Escalation =			
	Total Plant Investment			
	+	+		
	Owner's costs =	Owner's costs =		
Total As-Spent Capital	Total Capital Requirement	Total Capital Requirement		Total Installed Cost

BEC: Bare Erected Cost; EPCC: Engineering, Procurement & Construction Cost; IDC: Interest During Construction; AFUDC: Allowance for Funds Used During Construction.
[a] Total Overnight Cost is used interchangeably with Total Plant Cost in tables and discussions in GCCSI (2011).

power industry range from €60/tCO_2 to €90/tCO_2 (Carbon Capture and Storage Association, 2011). Specifically, for CO_2 capture from natural gas combined-cycle (NGCC) power plant's exhaust gas, it is between US \$48/tCO_2 – US\$111/tCO_2 (Rubin et al., 2015). This reflects the differences in the capital cost estimation methods used, in scopes of technical and economic analyses, and in the underlying assumptions. The effects of the differences in scopes, and underlying technical and economic assumptions can easily be recognised. However, to clearly understand how the different capital cost estimation methods affect the carbon capture cost estimates, it is important to evaluate the different capital cost estimation methods that are commonly used in the literature and their effects on the estimates obtained. There is a need to provide a cost estimation scheme that can give good cost estimates, yet open, transparent, straightforward, and relatively easy and fast to implement.

The methodologies developed for initial cost estimation by many organizations and institutions engaged in research towards innovations and advancement of the CCS technologies aimed at cost reduction are factorial techniques (Ali et al., 2019; IEAGHG, 2009; NETL, 2011; Rubin et al., 2013). This is because cost analyses at this level are mostly intended for concept screening and study/preliminary cost estimates. These factorial methods commonly employed for CCS cost estimates fall into Class 5 and Class 4 of the Association for the Advancement of Cost Engineering (AACE) (Christensen et al., 2005). Most of the methodologies applied are based on a Lang Factor for order of magnitude estimates, percentage or ratio of delivered-equipment cost or the cost element called the Bare Erected Cost (BEC), which includes all the equipment purchase costs (EPRI, 1993; Gardarsdottir et al., 2019; GCCSI, 2011; Nwaoha et al., 2018; Rubin et al., 2013). Cost estimates based on these methods assume a uniform installation factor applied on the sum of all the main plant equipment irrespective of the differences in their costs. However, every piece of equipment that makes up a chemical plant should not have the same installation factor (Gerrard, 2000). The installation factors for building a chemical plant that processes fluids and the one that processes solids should also be different. In each plant type, it is reasonable that the installation factors of less expensive equipment will be high, while very expensive equipment will have lower installation factors (Gerrard, 2000).

Cost estimates founded on BEC are mainly prepared by contractors based on equipment specifications (IEAGHG, 2009; NETL, 2011; Rubin et al., 2013). Table 1 shows capital cost nomenclature and aggregation method established on BEC for five different organisations (Rubin et al., 2013). Even though contractors generally prepare cost estimates that are accurate, such schemes are however challenging for other sectors except for those in the commercial world or governmental organizations. These cost estimates are normally not open and transparent, due to competitive advantage. They may also require well experienced cost engineers that probably work in engineering, procurement, and construction (EPC) companies to prepare. The list of equipment, basis of equipment

Table 2
EDF method's plant construction characteristic factors (PCCF).

Plant construction characteristics factors (PCCF)			
Instrument		**Insulation**	
Local instruments	0.36	No insulation	0.05
One control loop per main equipment	0.88	Heat insulation of utilities pipes	0.52
Two control loops per main equipment	0.94	Normal heat insulation	1.00
Tree control loops per main equipment	1.00	More than normal heat insulation	1.13
Electrical		Cold insulation of vessels and pipes	1.42
No electricity	0.09	**Ground preparation**	
Light	0.23	No ground preparation works	0.09
Light and electric power to building	0.82	Normal ground preparation without piling	1.00
Electric power from existing power supply	1.00	Normal ground preparation with piling	1.30
Electric power from new power supply	1.45	More than normal ground preparation without piling	2.16
Piping		More than normal ground preparation with piling	2.82
No piping	0.09	**Civil and buildings**	
Channels	0.27	No buildings	0.09
Thin pipes and pipes for utilities systems	0.67	Open on ground	0.28
Normal pipes and pipes for utilities	1.00	Open in a structure	0.78
Complex pipes and pipes for utilities	1.12	Closed structure	1.00
Big bore pipe and pipe for utilities	1.12	Insulated closed structure	1.60
Big bore and complex pipes and pipes for utilities	1.29	More than normal ground preparation with piling	2.82

dimensioning, or design are not usually disclosed. The assumptions or factors applied to derive both the total direct and total indirect costs do vary from one case to another (IEAGHG, 2009; NETL, 2011; Rubin et al., 2013). In addition, just like the Lang Factor and the closely related percentage of delivered-equipment costs methodologies, the same factor is applied on all the pieces of equipment (sum of all delivered equipment) irrespective of the wide differences that may exist in the purchase costs of the different main plant equipment.

Due to the importance of cost estimates in carbon capture and storage (CCS) processes, some attention has been given to harmonization of cost estimation methods and transparency, with focus on the power industry. A number of organizations have made efforts to develop their various procedures for estimating capital costs and guidelines towards achieving consistency and uniformity to a great extent in their various estimates of power plant and CCS costs (Rubin et al., 2013). Nevertheless, Rubin (2012) identified differences in underlying assumptions and methodology across these organizations which bring about confusion, instead of clarity, in capital cost estimates of CCS. The organizations include the International Energy Agency Greenhouse Gas Programme (IEAGHG), the U.S. Department of Energy's National Energy Technology Laboratory (DOE/NETL), and the Electric Power Research Institute (EPRI) (Rubin et al., 2013). Researchers (Roussanaly et al., 2019; Rubin, 2012; Rubin et al., 2013; Skagestad et al., 2014; van der Spek et al., 2019) have drawn attention to the inconsistencies in cost estimates and methods applied and emphasized significant methodological issues and factors which influence the total capital cost of the carbon capture plants (Ali et al., 2019). Rubin et al. (2013) did a review of some publications and pointed out the various cost elements, economic parameters, and assumptions that differ across these studies which influence the outcome.

Sinnott and Towler (2009) emphasized that disregarding to make appropriate correction due to material of construction is one of the foremost sources of errors in capital estimates. Yet, several methodologies based on these average overall plant's installation factors do not account for material of construction. Though, the material of construction is considered in the techniques founded on percentage of delivered equipment in these references (Sinnott and Towler, 2009; Smith, 2005).

Owing to all the limitations highlighted, we present a method we refer to as the Enhanced Detailed Factor (EDF) Method. This method has previously been documented by Ali et al. (2019), and it has been applied in another study by Aromada et al. (2020a). Ali et al. (2019) only presented the assumptions and some details about the method. Aromada et al. (2020) also only applied the method to study cost reduction potential by considering the use of different types of heat exchangers as the lean/rich heat exchanger. However, the most important aspect of the EDF method is the *installation factors* and *subfactors*. No study has shown how these factors affect the total plant cost. And to demonstrate this importance, it is essential to compare the effects of the EDF installation factors with the those of other methods in the open literature.

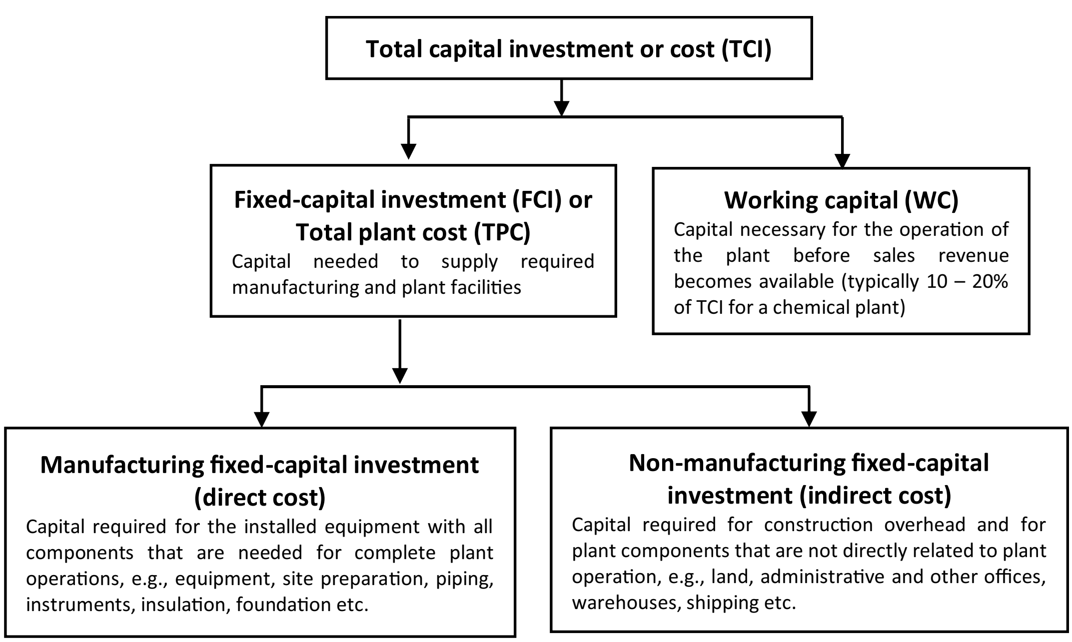

Fig. 1. Elements of total capital investment (Eldrup, 2021)

Table 3
Categories of factorial methods in literature

Factorial method categories	Basis/example	literature
Plant's overall installation factor	Lang factors	(Gerrard, 2000; Lang, 1948; Peters et al., 2004; Sinnott & Towler, 2009; Turton, 2018).
Equipment type factor	Hand factors	(Hand, 1958; Sinnott & Towler, 2009).
Percentage of delivered equipment cost	Percentage or ratios of delivered equipment usually free-on-board	(Gerrard, 2000; Mores et al., 2012; Peters et al., 2004; Sinnott & Towler, 2009; Smith, 2005).
Bare Erected Cost (BEC) module	Percentage or ratios of BEC	(IEAGHG, 2009; NETL, 2011; Nwaoha et al., 2018; Rubin et al., 2013)
Detailed factors	Individual factor and sub-factor method	(Gerrard, 2000; Husebye et al., 2012)
	EDF method	(Ali et al., 2019; Aromada et al., 2020a)

Another vital aspect of EDF method which is also new is the effect each plant's construction characteristic or nature will have on the capital cost. For example, using an existing building will reduce the civil cost, and reuse of a tank can reduce the cost, but all other cost will still be there. These new important factors which will affect the capital cost estimates are given in Table 2, and they are termed plant construction characteristic factors (PCCF) in this work. The PCCF was developed by Nils Eldrup based on industry experience and cost estimation in the pre-engineering phase, as well as experiences from construction. It was originally set up as a theory based on Gerrard (2000). Gerrard had this as an adjustment on each equipment, but that was thought to be too elaborate. Thus, the list was developed to cover the "factory description", and eventually, they have been tested on real plants and adjusted over a period of 25 years.

The PCCFs are applied on (i.e., multiply by) their corresponding subfactors both in the direct cost (material) and the engineering subfactors. For example, if there is no need for ground preparation, then, the subfactor "ground work" in the direct cost as well as the "engineering ground" subfactor in Table C2 in the Appendix C must be multiplied by the corresponding PCCF of 0.09 in Table 2 under "ground preparation".

Table 4
Material factors for EDF method.

Material of construction	Material factor, f_M
Carbon steel	1.00
316 stainless steel (machined)	1.30
316 stainless steel (welded)	1.75
Glass-reinforced plastic	1.40
Exotic material (machined)	1.75
Exotic material (welded)	2.50

Table 5
Material factors for Hand factors method and for the percentage of delivered equipment factorial technique in (Sinnott & Towler, 2009)

Material of construction	Material factor, f_M
Carbon steel	1.00
Aluminium and bronze	1.07
Cast steel	1.10
304 stainless steel	1.30
316 stainless steel	1.30
321 stainless steel	1.50
Hastelloy	1.55
Monel	1.65
Nickel and Inconel	1.70

Table 6
Material factors for the percentage of delivered equipment factorial technique in (Smith, 2005)

Material	Material factor, f_M		
	Average	Pressure vessels and distillation columns	Shell and tube heat exchanger
Carbon steel	1.0	1.0	1.0
Aluminium	1.3		
Stainless steel (low grades)	2.4	2.1	
Stainless steel (high grades)	3.4	3.2	
Hastelloy C	3.6		
Monel	4.1	3.6	
Nickel and Inconel	4.4		
Titanium	5.8	7.7	
Nickel		5.4	
Inconel		3.9	
CS Shell, aluminium tubes			1.3
CS Shell, Monel tubes			2.1
CS Shell, SS (low grades) tubes			1.7
SS (low grades) shell and tubes			2.9

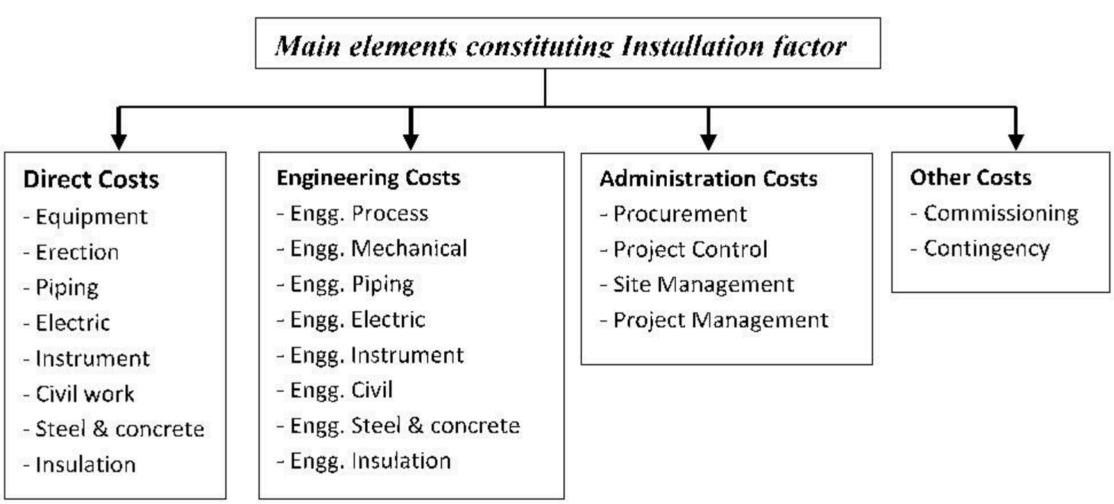

Fig. 2. Main elements of the Enhanced Detailed Factors (Ali et al., 2019)

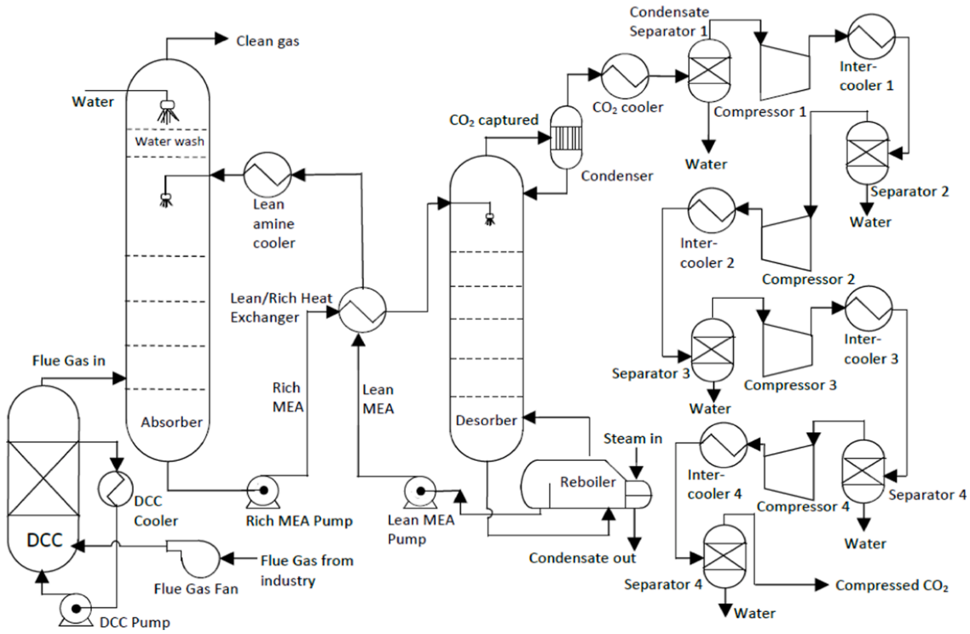

Fig. 3. Process flow diagram of a standard amine-based CO_2 capture process (Aromada et al., 2020a)

Table 7
Specifications and assumption for simulation

Parameter	Value	Source
CO_2 capture efficiency [%] 85 (Andersson et al., 2016)		
Flue gas		
Temperature [°C]	80	(Aromada et al., 2020a)
Pressure [kPa]	110	(Aromada et al., 2020a)
CO_2 mole-fraction	0.0375	(Øi, 2007)
H_2O mole-fraction	0.0671	(Øi, 2007)
N_2 mole-fraction	0.8954	Calculated
Molar flow rate [kmol/h]	85000	(Øi, 2007)
Temperature of flue gas into absorber [°C]	40	(Aromada & Øi, 2015)
Pressure of flue gas into absorber [kPa]	110	(Ali et al., 2019)
Lean MEA		
Temperature [°C]	40	(Øi, 2007)
Pressure [kPa]	101	(Aromada & Øi, 2015)
Molar flow rate [kmol/h]	101595	Calculated
Mass fraction of MEA [%]	29	(Øi, 2007)
Mass fraction of CO_2 [%]	5.4	(Øi, 2007)
Absorber		
No. of absorber stages	15	(Aromada & Øi, 2017)
Absorber Murphree efficiency [%]	11- 21	(Ali et al., 2019)
ΔT_{min} lean/rich heat exchanger [°C]	10	(Karimi et al., 2011)
Desorber		
Number of stages	10	(Aromada & Øi, 2017)
Desorber Murphree efficiency [%]	50	(Ali et al., 2019)
Pressure [kPa]	200	(Øi, 2007)
Reflux ratio in the desorber	0.3	(Øi, 2007)
Temperature into desorber [°C]	103.5	
Reboiler		
Reboiler temperature [°C]	120	(Øi, 2007)
Saturated steam temperature [°C]	160	(Kallevik, 2010)
Exit temperature of steam [°C]	151.8	(Kallevik, 2010)
CO_2 compression final pressure [kPa]	11100	(Ahn et al., 2013)

Table 8
Equipment dimensioning factors and assumptions

Equipment	Basis/Assumptions	Sizing factors
DCC Unit	Velocity using Souders-Brown equation with a k-factor of 0.15 m/s (Yu, 2014, pp. 97). TT =15 m, 1 m packing height/stage (4 stages) (Aromada et al., 2020a)	All columns: Tangent-to-tangent height (TT), Packing height, internal and outer diameters (all in [m])
Absorber	Superficial velocity of 2 m/s, TT=40 m, 1 m packing height/stage (15 stages) (Aromada et al., 2020a).	
Desorber	Superficial velocity of 1 m/s, TT=22 m, 1 m packing height/stage (10 stages) (Aromada & Øi, 2017).	
Packings	Structured packing: SS316 Mellapak 250Y (Aromada & Øi, 2017).	See DCC Unit, absorber and desorber
Lean/rich heat exchanger	U = 0.73 kW/m^{2}K for FTS-STHX (Nwaoha et al., 2018).	Heat transfer area, A [m^2]
Reboiler	U = 1.20 kW/m^{2}K for U-tube kettle type, based on (Peters et al., 2004)	
Condenser	U = 1.00 kW/m^{2}K for U-tube STHX, based on (Aromada et al., 2020a)	
Coolers	U = 0.8 kW/m^{2}K for U-tube STHX, (Aromada et al., 2020a)	
Intercooler pressure drop	0.5 bar [20] (Aromada et al., 2020a)	U-tube HX
Pumps	Centrifugal	Flowrate [l/s] and power [kW]
Flue gas fan	Centrifugal	Flow rate [m^3/h]
Compressors	Centrifugal; 4-stages (Ahn et al., 2013); Final pressure = 110 bar (Ahn et al., 2013); pressure ratio = 2.8	Power [kW] and flowrate [m^3/h]
Separators	Vertical vessels; vessel diameter using Souders-Brown equation, a k-factor of 0.101 m/s (CheGuide, 2017; Yu, 2014); corrosion allowance of 0.001 m; joint efficiency of 0.8; stress of 2.15×10^8 Pa [45]; TT =3D$_o$ (CheGuide, 2017)	Outer diameters (D$_o$); tangent-to-tangent height (TT), (all in [m])

Table 9
Assumptions for capital cost estimation

Parameter	Value	Source
CAPEX	Total plant cost (TPC)	(Aromada et al., 2020a)
Cost year	2018, first quarter	Assumed
Cost data year	2018, first quarter	(AspenTech-A.I.C.E.)
Currency conversion (€ to NOK)	10.13, January 25, 2020	(NorgesBank, 2020)
Cost currency	Euro [€]	Assumed
Plant location	Rotterdam	Default
Project life	25 years	(IEAGHG, 2009)
Duration of construction	2 years	(Aromada et al., 2020a)
Discount rate	8 %	(IEAGHG, 2009)
Material conversion factor (SS to CS)	1.75 Welded; 1.30 Machined	(Aromada et al., 2020a)
Annual maintenance	3% of CAPEX	(Karimi et al., 2011)
FOAK or NOAK	NOAK	(IEAGHG, 2009)

Table 10
Operating cost data

	Unit	Value/unit*	Reference
Operating hours/ year	Hours/ year	8000	(Aromada & Øi, 2017)
Electricity	€/kWh	0.078	(Luo, 2016)
Steam	€/kWh	0.032	25% of electricity cost
Cooling water	€/m^3	0.022	(Ali et al., 2019)
Water (process)*	€/m^3	0.203	(IEAGHG, 2009)
MEA*	€/m^3	1516	(Luo, 2016)
Maintenance	€	3% of CAPEX	(Karimi et al., 2011)
Operator	€	80,414 (× 6 operators)	(Ali et al., 2019)
Engineer	€	156,650 (1 engineer)	(Ali et al., 2019)

**The values have been escalated to January 2018*

This ensures a more realistic capital cost estimation.

In the EDF method, different total equipment installation factors and subfactors are applied to different equipment based on their various costs (Free On Board-FOB). The method has installation factors and subfactors prepared in carbon steel (CS) and are more detailed. A very costly equipment has low installation factor, and a less expensive one has a higher installation factor. Where an expensive material such as stainless steel is used to manufacture any of the main plant equipment, the appropriate correction due to the material is implemented, and the mode of construction (welded or machined) is also considered. It also includes a location factor. The method treats every piece of equipment as a separate project. It shows the individual contribution of each piece of equipment to the capital cost, thereby highlighting the major cost drivers for optimisation. Consequently, it is also suitable for capital cost estimation for retrofits or modification projects, which is an advantage. One does not need to be an experienced process engineer or cost engineer to use the EDF method, because it does not depend on individual persons' judgement. The EDF method layout makes the estimates more transparent, and it becomes easier to communicate between the cost estimator and the process developer. That is, this method is very good during the process development because the process engineer can see the effect of his choices very quickly.

1.1. Scope of analysis

Fig. 1 presents the main elements of total capital investment (TCI) or cost. The interest in this study is mainly on equipment installed costs, to check the impacts of the installation factors in each of the selected methods on the total equipment installed costs. Therefore, the capital investment or expenses (CAPEX) in this work is limited to the total plant cost (TPC). This comprises the sum of all equipment installed costs. In addition, the methods studied are limited to only ratios or factorial capital cost estimation techniques generally used for concept screening and feasibility studies (Class 5 and Class 4 of the AACE classification).

Even though the location factor is important and will always have a large effect on the TPC, this is not considered it this study. This is because all the methods are used to estimate TPC of the same CO_2 capture process plant, to assess the impacts of the different installation factors on TPC and individual equipment installed costs. The location of Rotterdam is assumed. Cost escalations was not performed because the equipment cost year (2018) is also assumed as the year of purchase. In addition, size adjustment was not necessary at any point since equipment cost for each dimensioned main plant equipment was obtained directly from Aspen In-Plant Cost Estimator V11. The impact of the plant construction characteristic situation was also evaluated.

2. Capital cost estimation methodologies in literature

Factorial methods which are commonly used for producing study and preliminary estimates at the early stage of projects are founded on historical knowledge of relative equipment purchase costs and the necessary activities and items to fully build a chemical plant (Gerrard, 2000). They follow the bottom-up approach and are broken down into different categories of expenditures that are necessary to be incurred to fully install the purchased or delivered main plant equipment (Nwaoha et al., 2018).

The starting point for all factorial methods is a list of all the major plant equipment, usually through the plant's process flowsheet (Ali et al., 2019; Sinnott and Towler, 2009). The purchase costs of equipment can be obtained from the following in the order of decline in accuracy (Eldrup, 2021):

1. Current price quotes from equipment vendors (expensive for the provider)
2. Budget quotes/offer (±25% variation)
3. Design and costing (need experienced professionals/experts)
4. Cost data from previously purchased equipment of the same type (in-house data)
5. Commercial databases (e.g., Aspen In-Plant Cost Estimator)
6. Equipment cost correlations in form of graphs or software:
   - Book (cheap but old data)

Table 11
Comparison of simulation results with literature

	CO_2 concentration	Capture rate	Absorber packing stages	ΔT_{min}	Rich loading	Reboiler specific heat
	mol%	*%*	*m*	*°C*		*GJ/tCO₂*
This work	3.75	84.99	15	5	0.50	3.54
		85.06	15	10	0.50	3.71
(Øi, 2007)	3.75	85.00	10	10	n.a.	3.65
(Amrollahi et al., 2012)	3.80	90.00	13	8.5	0.47	3.74
(Nikolett Sipöcz & Tobiesen, 2012)	4.40	90.00	26.9*	n.a.	0.47	3.97
(N. Sipöcz et al., 2011)	4.20	90.00	26.9*	10	0.47	3.93
(Dutta et al., 2017)	4.16	90.00	27.2*	5	0.47	3.70

*Not defined if it is packing height or shell tangent-tangent height.

Table 12
Total plant cost/CAPEX estimated with EDF method

Equipment	Mat.	Equip. cost/ unit, k€	Mat. Factor	Equip. cost in CS, k€	Equip. cost in CS, kNOK	Install. factors, CS	Total install. factors	Installed cost in original mat./ unit, k€	Nos.	Total equip. cost in original mat., k€	Total installed cost in original mat., k€
Column no.: 1	2	3	4	5	6	7	8	9	10	11	12
Flue gas fan	CS	1 386	1.00	1 386	14 039	4.44	4.44	6 153	2	2 772	12 307
DCC unit shell	SS	2 552	1.75	1 458	14 772	4.44	5.50	8 017	1	2 552	8 017
DCC-unit packing	SS	2 019	1.75	1 153	11 685	4.44	5.50	6 341	1	2 019	6 341
DCC pump	SS	855	1.30	658	6 662	4.44	4.86	3 198	1	855	3 198
DCC cooler	SS	357	1.75	204	2 064	4.93	6.04	1 230	2	713	2 461
Absorber shell	SS	4 714	1.75	2 694	27 287	3.59	4.56	12 277	2	9 428	24 553
Absorber packing	SS	5 541	1.75	3 167	32 077	3.59	4.56	14 431	2	11 083	28 863
Desorber shell	SS	1 404	1.75	802	8 125	4.44	5.50	4 409	1	1 404	4 409
Desorber packing	SS	1 309	1.75	748	7 575	4.44	5.50	4 111	1	1 309	4 111
Lean/rich HX	SS	564	1.75	322	3 266	4.93	6.04	1 948	20	11 286	38 953
Reboiler	SS	518	1.75	296	2 996	4.93	6.04	1 786	3	1 553	5 358
Condenser	SS	127	1.75	72	732	7.20	8.57	620	1	127	620
Lean MEA cooler	SS	372	1.75	212	2 152	4.93	6.04	1 283	2	743	2 566
Rich pump	SS	197	1.30	152	1 535	6.10	6.60	999	1	197	999
Lean pump	SS	230	1.30	177	1 791	6.10	6.60	1 166	1	230	1 166
Compressor 1	CS	4 072	1.00	4 072	41 247	3.59	3.59	14 618	1	4 072	14 618
Compressor 2	CS	2 370	1.00	2 370	24 005	3.59	3.59	8 507	1	2 370	8 507
Compressor 3	CS	1 510	1.00	1 510	15 291	3.59	3.59	5 419	1	1 510	5 419
Compressor 4	CS	1 777	1.00	1 777	17 999	3.59	3.59	6 379	1	1 777	6 379
Intercooler 1	SS	62	1.75	36	361	9.13	10.72	382	1	62	382
Intercooler 2	SS	61	1.75	35	350	9.13	10.72	371	1	61	371
Intercooler 3	SS	64	1.75	36	369	9.13	10.72	390	1	64	390
Intercooler 4	SS	103	1.75	59	597	7.20	8.57	506	1	103	506
T-Cooler	SS	23	1.75	13	134	9.13	10.72	142	1	23	142
Condensate cooler	SS	386	1.75	221	2 234	4.93	6.04	1 332	1	386	1 332
Condensate separator	SS	161	1.75	92	933	7.20	8.57	790	1	161	790
Separator 1	SS	108	1.75	62	625	7.20	8.57	529	1	108	529
Separator 2	SS	124	1.75	71	719	7.20	8.57	608	1	124	608
Separator 3	SS	131	1.75	75	759	7.20	8.57	643	1	131	643
Separator 4	SS	156	1.75	89	901	7.20	8.57	763	1	156	763
CW pump 1	CS	110	1.00	110	1 113	6.10	6.10	670	1	110	670
CW pump 2	CS	172	1.00	172	1 744	6.10	6.10	1 050	1	172	1 050
CW pump 3	CS	99	1.00	99	1 006	6.10	6.10	606	1	99	606
CW pump 4	CS	18	1.00	18	178	9.13	9.13	161	1	18	161
CW pump 5	CS	18	1.00	18	178	9.13	9.13	161	1	18	161
CW pump 6	CS	18	1.00	18	178	9.13	9.13	161	1	18	161
CW pump 7	CS	26	1.00	26	265	9.13	9.13	239	1	26	239
T-pump	CS	10	1.00	10	97	15.03	15.03	144	1	10	144
CO_2 pump	SS	163	1.30	125	1 269	6.10	6.60	826	1	163	826
Total equipment cost (TEC) and Total plant cost (TPC)										**58 008**	**189 317**

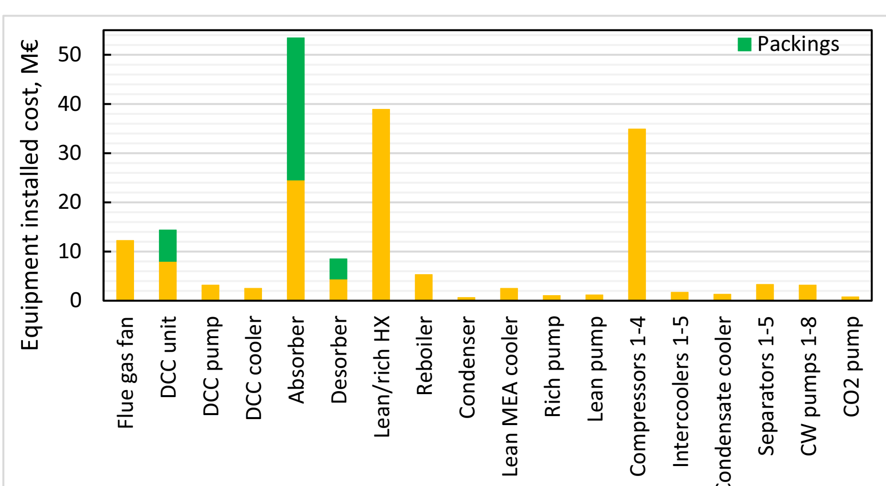

Fig. 4. Overview of cost contribution of the main plant equipment to the capital cost (TPC)

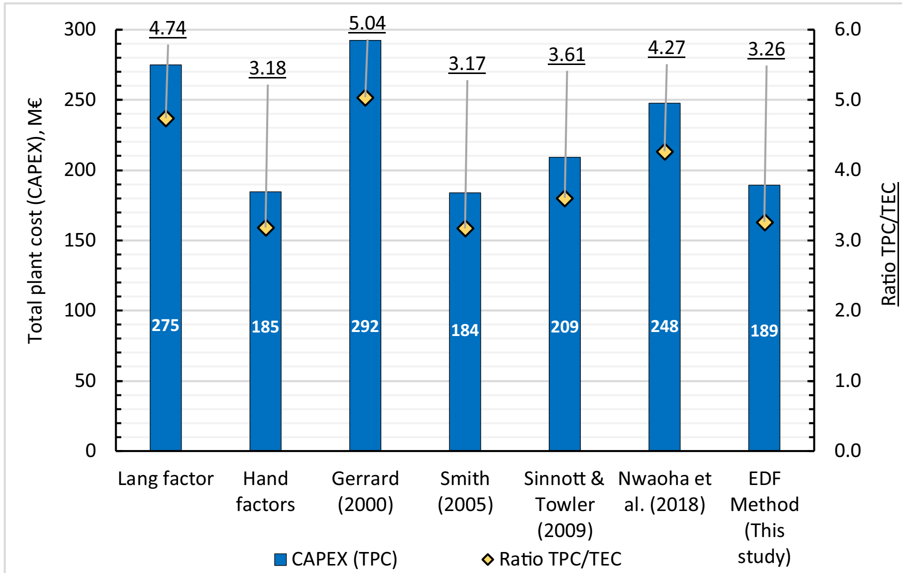

Fig. 5. Total plant cost and ratio of total plant cost to total equipment cost for 85% CO_2 capture plant

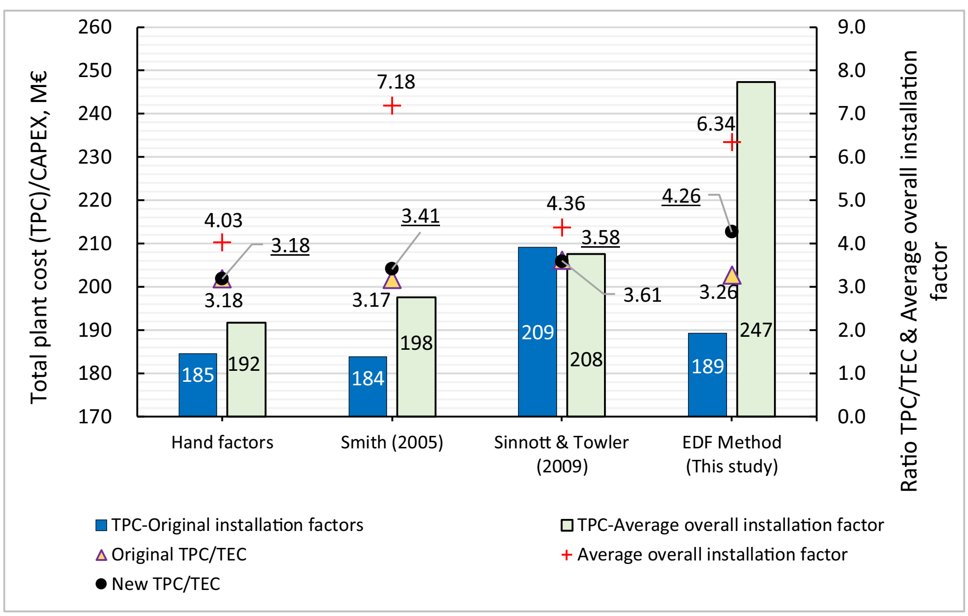

Fig. 6. Original total plant costs (TPC) and TPC based on average overall installation factors for the base case

- Internet (quality of data may be doubtful)

In this work, we categorised the main factorial cost estimation techniques in literature as shown in Table 3. To compare the installation factors of EDF method with the other methods, which was not done in Ali et al. (2019), we selected at least one method from each of the categories as listed below:

- Plant's overall installation factor:
- Lang factor method (Lang, 1948)
- Specific equipment type factor:
- Hand factor method (Hand, 1958)
- Percentage of delivered equipment cost:
- Sinnott and Towler (2009)
- Smith (2005)
- Gerrard (2000) – same installation factors as Peters et al. (2004)
- Bare Erected Cost (BEC) module factor:
- Nwaoha et al. (2018)
- Detailed factor:
- EDF method (Ali et al., 2019)

The EDF method is similar to the individual and sub-factors method in Gerrard (2000). However, the EDF method installation factors are more details. They include indirect cost, commissioning, and contingency. It has been tested and adjusted against built plants. The installation factors of EDF method are updated every two years, to reflect the impacts of inflation and recent realities in chemical plant construction or modification projects. Nevertheless, older versions of EDF installation factors lists can still be used with the aid of cost price indices (CPI), and the equipment installed costs can be adjusted to today also using CPI. Full details of the installation factors in Husebye et al. (2012) were not published, so, they cannot be used by others.

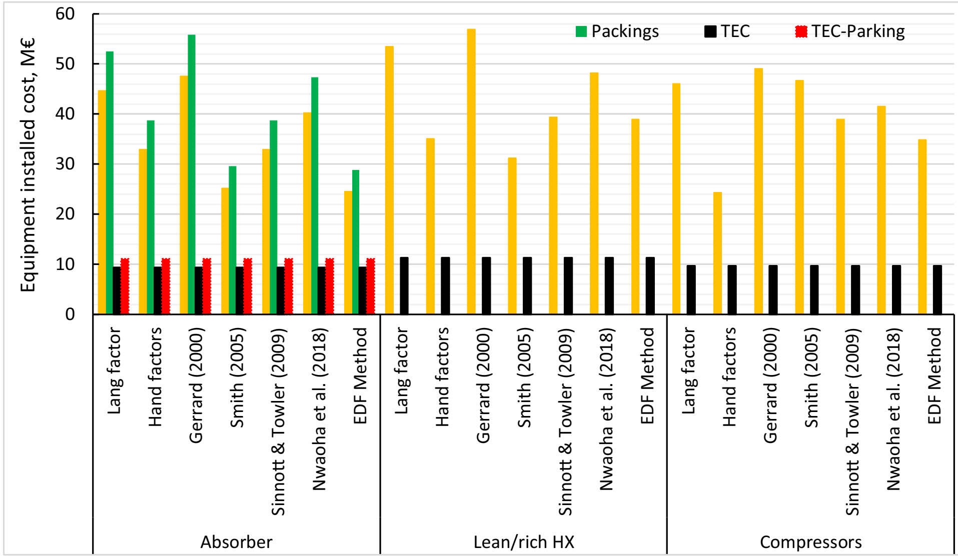

Fig. 7. Comparison of the installed costs of the most expensive equipment

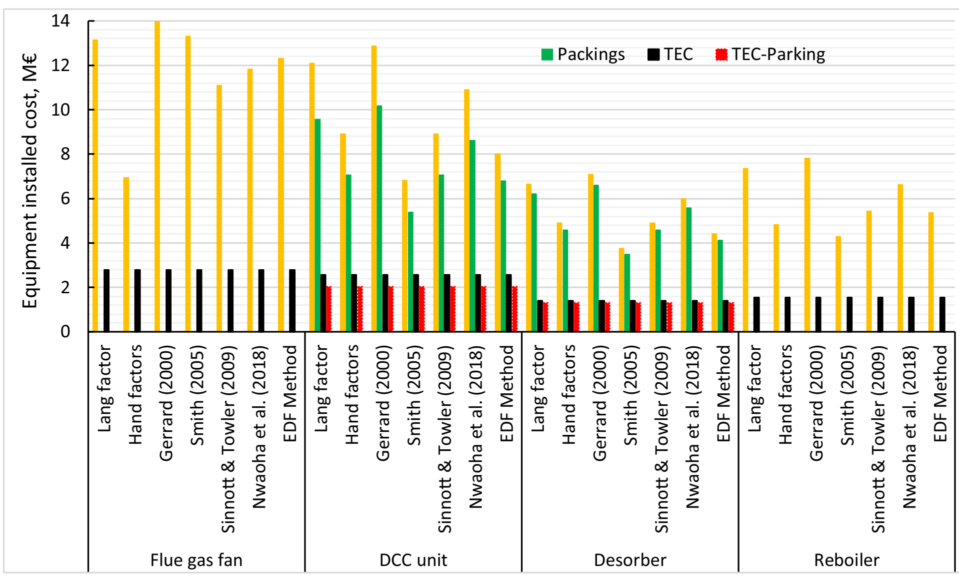

Fig. 8. Comparison of the installed costs of expensive equipment

2.1. The Enhanced Detailed Factors (EDF) method

At the early stage of capital cost estimation, the EDF method achieves a high level of accuracy (Ali et al., 2019). It highlights the contribution of individual equipment to TPC, therefore revealing which equipment needs to be optimised. It can be applied in techno-economic assessment of new plants, new technologies and extension or modification projects for an existing plant (Ali et al., 2019).

To use the EDF method, the scope of the project must be specified, technical and economic assumptions must be defined. If necessary, location factor may be applied. There may be a need for currency conversion and cost escalation from one year to another. If there is a need to estimate the total capital investment (TCI), then, the working capital can be calculated, as shown in Fig. 1. The EDF method comprises the following steps to estimate the TPC (Ali et al., 2019):

1 Prepare a simple flowsheet of the plant and list the major plant equipment.
2 Compute the material and energy balance of the process either through process simulations or by hand calculation.
3 Perform equipment dimensioning/sizing based on the material and energy balances.
4 Estimate the cost of each piece of equipment from a reliable source. In this work, we used Aspen In-Plant Cost Estimator version 11database.
5 It is convenient to list the equipment in a spreadsheet with their purchase costs.
6 Convert the purchase cost of each piece of equipment in material other than carbon steel to its corresponding cost in carbon steel using the appropriate material factor in Table 4. This is because the installation factors are in CS, as it is for Hand factors and in Sinnott and Towler (2009) and Smith (2005).
7 Obtain the appropriate total installation factor in CS for each piece of equipment.
8 Correction of specific subfactors may be required based on the nature or characteristics of the construction works. For example, if more than the normal heat insulation is required due to very

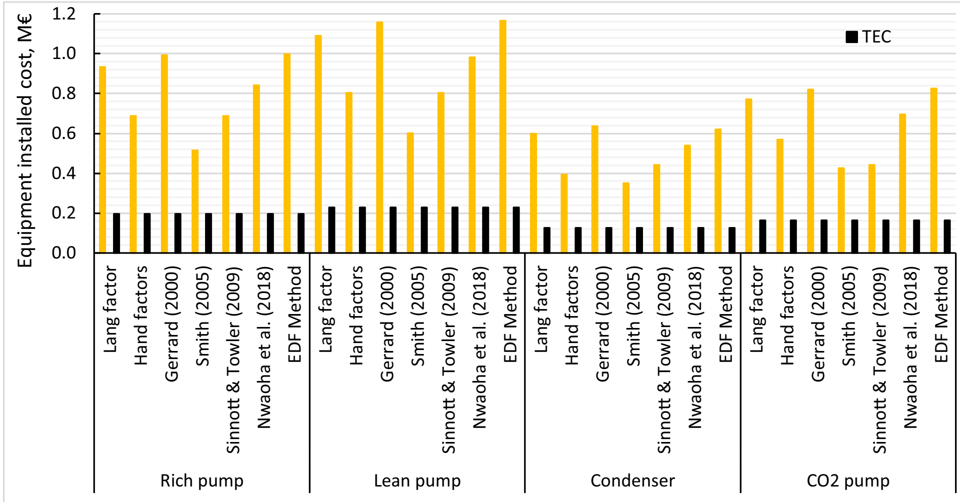

Fig. 9. Comparison of the installed costs of less expensive equipment

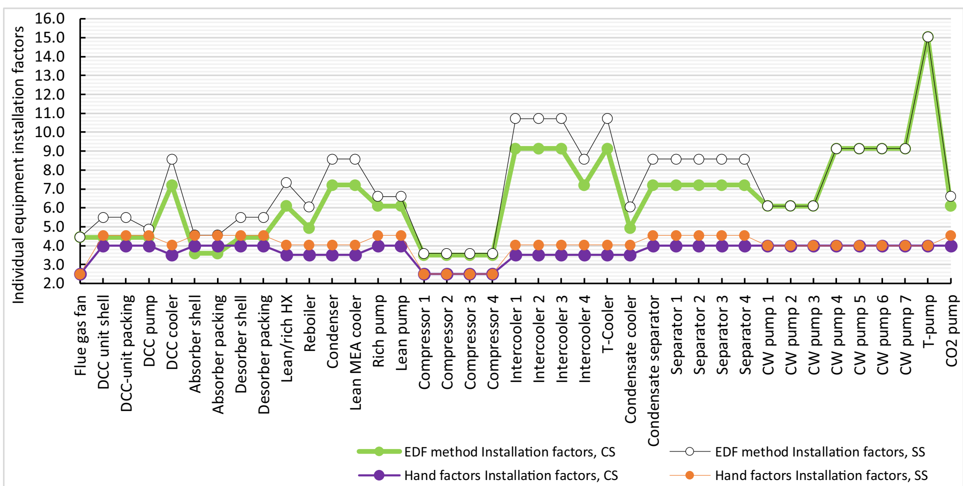

Fig. 10. Comparison of Hand factors with EDF installation factors for each piece of equipment

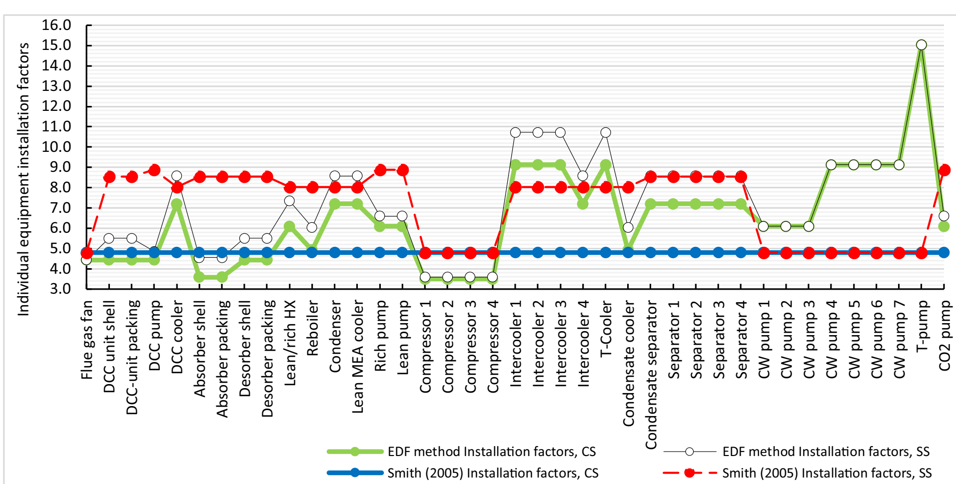

Fig. 11. Comparison of PDE-F in Reference (Smith, 2005) with EDF installation factors for each piece of equipment

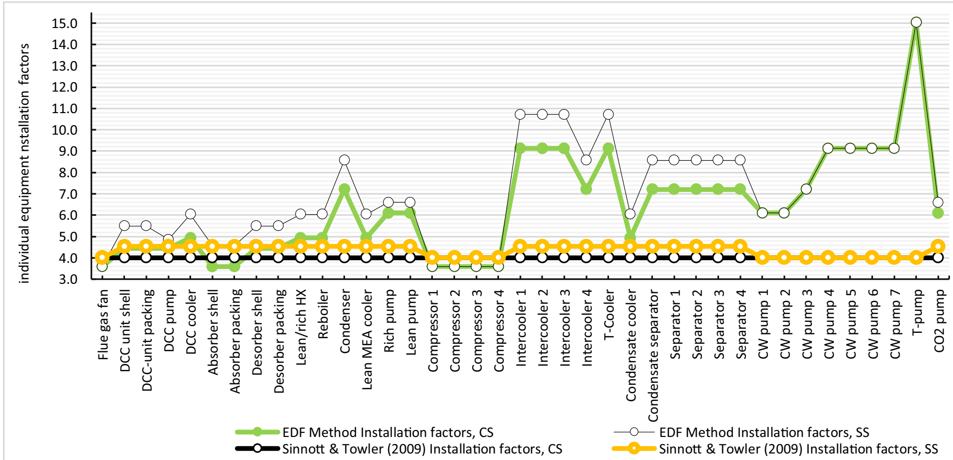

Fig. 12. Comparison of PDE-F in Reference (Sinnott &Towler, 2009) with EDF installation factors for each piece of equipment

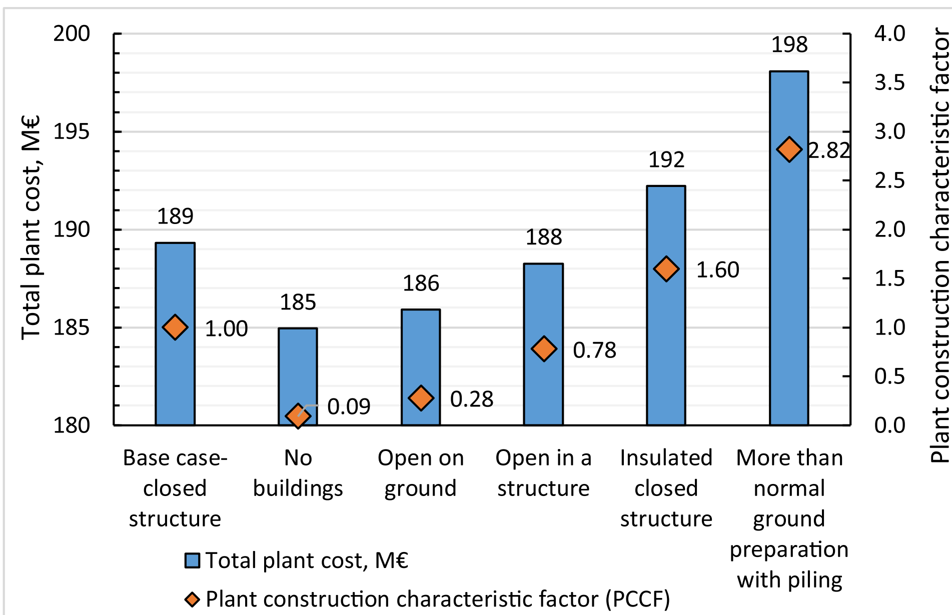

Fig. 13. Effects of EDF method's plant construction characteristic factors (PCCF) on the TPC

cold weather in the plant specific location, then, the insulation subfactor in both direct cost and engineering subfactors in Table C1 or Table C2 in the Appendix C must be corrected by multiplication with the corresponding specific construction factor in Table 2.

9 Calculate the installation factors for all equipment in another materials (SS316 in this work) accounting for the material and piping.

10 Estimate an equipment installed cost, multiply the cost of each piece of equipment in CS by the total installation factor in CS. For the equipment in another materials (SS316), multiply the cost of each piece of equipment in CS by the total installation factor in the other material (SS316). In this work, Table C1 in Appendix C was used, so, the costs need to be converted back to Euros. Subsequent works can use the installation factors in Table C2.

11 For any equipment that has more than one piece or unit, multiply it by the number of units to obtain the total installed cost for that equipment.

12 The total plant cost is the sum of all the equipment installed cost.

It is important to state that the previous EDF installation factors list (up to 2018) were prepared in Norwegian kroner (NOK), thus, currency conversion to NOK was necessary when the equipment is in another currency. The installation factors are for equipment in carbon steel (CS), therefore, conversion of cost of equipment in other materials such as stainless steel to cost in CS is necessary. This is simply done as follows using an appropriate factor in Table 4:

$$C_{Eq.,\ CS} = \frac{C_{other\ mat.}}{f_M} \tag{4}$$

Where,

$C_{Eq.,CS}$ = cost of equipment in carbon steel

$C_{Eq.,\ other\ mat.}$ = cost of equipment in other material

f_M = material factor for converting cost in other materials to cost in CS

After converting the equipment cost in SS to CS, the appropriate total installation factors for the piece of equipment in CS can be obtained from Table C1 or Table C2 in Appendix C. This can be represented as:

$$F_{T,CS} = f_{direct} + f_{engineering} + f_{administration} + f_{commissioning} + f_{contingency} \tag{5}$$

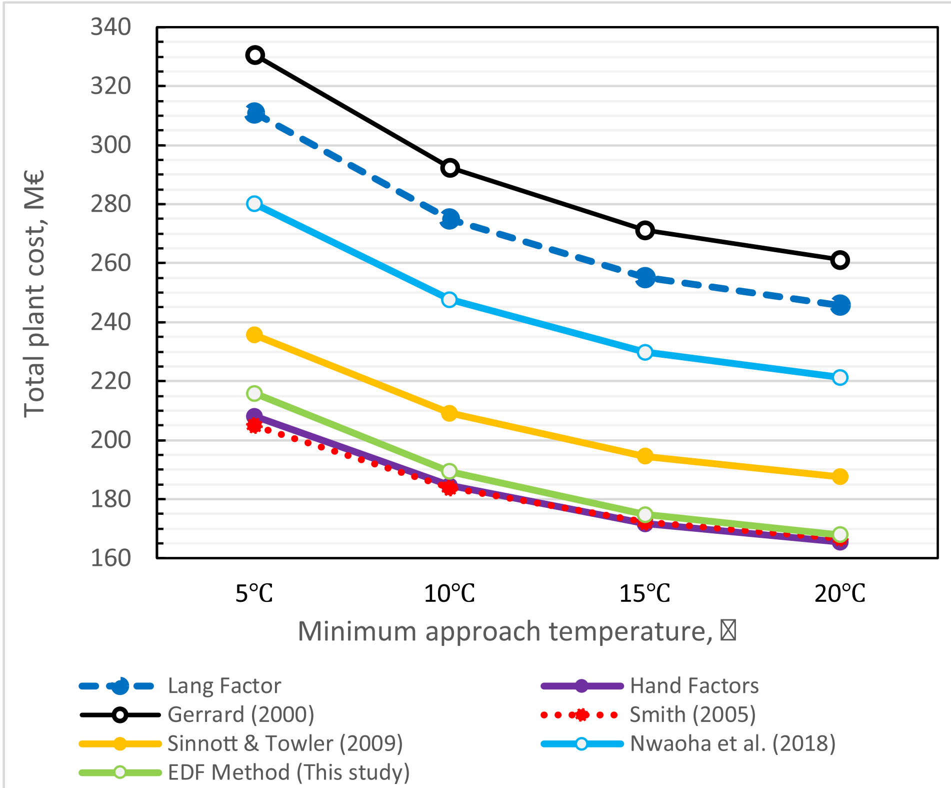

Fig. 14. Comparison of capital costs estimated from the different factorial methods for CO_2 capture plant

For equipment bought in other materials, the installation factors need to be converted from CS back to the original material. It is important to understand that it is only the equipment material and piping that will be affected. Therefore, the final EDF installation factor for any piece of equipment in other material can be estimated by subtracting the equipment factor (usually 1) and piping sub-factor in CS from $F_{T,CS}$, then add the equipment subfactor and piping sub-factor in the other material as shown in equation (6), and rearranged to (7):

$$F_{T,\ other\ mat.} = F_{T,\ CS} - (f_{Eq.} + f_{pp,CS}) + f_M(f_{Eq.} + f_{pp,CS}) \tag{6}$$

$$F_{T,\ other\ mat.} = F_{T,\ CS} + (f_M - 1).(f_{Eq.} + f_{pp,CS}) \tag{7}$$

The installed cost of each piece of equipment in CS, and in other materials and the TPC can then be estimated using equation (8), (9) and (10) respectively:

$$C_{EIC,\ CS} = C_{Eq.,\ CS}.F_{T,\ CS} \tag{8}$$

$$C_{EIC,\ other\ mat.} = C_{Eq.,\ CS}.F_{T,\ other\ mat.} \tag{9}$$

$$TPC = \sum(All\ equipment\ installed\ costs) \tag{10}$$

The equipment cost year in this work is 2018 and the capital cost year is also assumed to be 2018. Thus, there was no need for cost escalation. The list of EDF installation factors for 2016 – 2018 attached as Table C1 in Appendix C was used in this study. The recently updated list, which is in Euros (€) is also attached as Table C2 in Appendix C for anyone who would like to use our method. The main elements that constitute the EDF installation factors are shown in Fig. 2.

2.2. Material factors of different approaches

The EDF scheme, Hand factors and Percentage of Delivered Equipment (%DEQ) technique in Sinnott and Towler (2009), and in Smith (2005) are presented in Tables 4-6 respectively.

3. Process specifications and simulation, equipment sizing and assumptions

3.1. Process specifications and simulation

The flue gas treated in this work is from a natural gas combined cycle (NGCC) power plant (Øi, 2007). The standard amine-based CO_2 absorption and desorption process is used for this study. The simplified process flow diagram (PFD) is shown in Fig. 3. Pre-treatment of the flue gas is not considered, the process commences from the flue gas fan in the precooling section, to the absorption and desorption process and ends with the CO_2 compression section which is model based on the work of Ahn et al. (2013). Transportation and storage of the captured CO_2 is not included in this work. Estimates of CO_2 transport and storage can be found in Andersson et al. (2016), Rubin and Zhai (2012), and Tel-Tek (2012).

The flowsheet is simulated in Aspen HYSYS Version 10 for 85% CO_2 removal based on the specifications in Table 7. The Aspen HYSYS flowsheet is attached as Fig. A1 in Appendix A. All the main plant equipment makes up the scope of the capital cost estimate. The simulation strategy is the same as described in Aromada et al. (2020a). The absorption and desorption columns were simulated as equilibrium stages (Murphree efficiency) (Aromada and Øi, 2015; Øi, 2007). The specified number of stages in the absorption and desorption columns are the cost optimum in Aromada and Øi (2017). Each column stage is assumed to be 1 m high. Murphree efficiencies of 0.21 – 0.11 were specified from the top to bottom of the absorber column as in Ali et al. (2019) and Aromada et al. (2020a). A constant Murphree efficiency of 0.5 was set for all stages in the desorption column (Ali et al., 2019; Aromada et al., 2020a). The captured CO_2 gas was assumed to undergo four-stage compression as in Ahn et al. (2013). The final four-stage compression pressure is 75.9 bar with a CO_2 purity of 99.8%. A CO_2 pump is used to raise the CO_2 stream pressure to 110 bar, which is cooled down to 31°C.

Table 13
Impact of the different methods on the CO_2 capture plant's economic performance

	EDF method	Hand factors	Smith (2005) [% DEQ]	Sinnott & Towler (2009) [% DEQ]	Nwaoha et al. (2018) [BEC]	Lang factor	Gerrard (2000) [% DEQ]
	M€						
	Minimum approach temperature = 5 °C						
CAPEX (TPC)	215.90	208.12	204.82	235.66	280.11	310.94	330.62
Annualized CAPEX	20.82	20.07	19.75	22.72	27.01	29.98	31.88
Fixed OPEX	7.12	6.88	6.78	7.71	9.04	9.97	10.56
Variable OPEX	38.47	38.47	38.47	38.47	38.47	38.47	38.47
Total annual cost	66.41	65.42	65.01	68.91	74.53	78.42	80.91
	€/tCO_2						
CO_2 capture cost	69.5	68.5	68.0	72.1	78.0	82.1	84.7
	Minimum approach temperature = 10 °C						
	M€						
CAPEX (TPC)	189.32	184.60	183.88	209.17	247.70	274.96	292.36
Annualized CAPEX	18.25	17.80	17.73	20.17	23.88	26.51	28.19
Fixed OPEX	6.32	6.18	6.16	6.91	8.07	8.89	9.41
Variable OPEX	57.81	39.55	39.55	39.55	39.55	39.55	39.55
Total annual cost	64.13	63.53	63.44	66.63	71.51	74.95	77.15
	€/tCO_2						
CO_2 capture cost	67.2	66.5	66.4	69.8	74.9	78.5	80.8
	Minimum approach temperature = 15 °C						
	M€						
CAPEX (TPC)	174.80	171.63	172.20	194.51	229.80	255.09	271.23
Annualized CAPEX	16.85	16.55	16.60	18.76	22.16	24.60	26.15
Fixed OPEX	5.88	5.79	5.81	6.47	7.53	8.29	8.78
Variable OPEX	40.52	40.52	40.52	40.52	40.52	40.52	40.52
Total annual cost	63.26	62.86	62.93	65.75	70.21	73.41	75.45
	€/tCO_2						
CO_2 capture cost	66.3	65.9	65.9	68.9	73.6	76.9	79.1
	Minimum approach temperature = 20 °C						
	M€						
CAPEX (TPC)	167.88	165.49	166.68	187.56	221.30	245.66	261.20
Annualized CAPEX	16.19	23.69	16.07	18.09	21.34	23.69	25.19
Fixed OPEX	5.68	8.01	5.64	6.27	7.28	8.01	8.48
Variable OPEX	42.02	42.02	42.02	42.02	42.02	42.02	42.02
Total annual cost	63.88	73.72	63.73	66.37	70.64	73.72	75.68
	€/tCO_2						
CO_2 capture cost	67.0	66.7	66.9	69.7	74.1	77.4	79.4

3.2. Equipment dimensioning and assumptions

Mass and energy balances from the process simulations were used for sizing the equipment listed above. The dimensioning approach is the same for previous studies at the University of South-Eastern Norway (USN) (Aromada et al., 2020a, 2020b; Aromada and Øi, 2017; Kallevik, 2010). The dimensioning factors and assumptions are summarised in Table 8. Since CO_2 is an acid gas with risk of corrosion, stainless steel SS316 is assumed for all equipment except the flue gas fan, the casing of the compressors and the cooling water pumps which are assumed to be manufactured from carbon steel. The dimensions and purchase costs of all the equipment are given in Tables B1-B4 in Appendix B.

3.3. Capital Cost Estimation Assumptions

The capital cost estimates in this work using the selected seven factorial methods are limited to the total plant cost also referred to as fixed-capital investment. For simplicity, CO_2 capture cost is the cost metric used in this work. Other important cost metrics mostly used is the levelized cost or levelized cost of electricity (LCOE) for power plants' cost estimates, and CO_2 avoided cost (Rubin et al., 2015). The annual capital cost, annualized factor, total annual cost, and CO_2 capture cost were estimated using Eqs. (11), (12), (13) and (14) respectively.

$$Annualised\ CAPEX\left(\frac{€}{yr}\right) = \frac{CAPEX}{Annualised\ factor} \quad (11)$$

$$Annualised\ factor = \sum_{i=1}^{n}\left[\frac{1}{(1+r)^n}\right] \quad (12)$$

$$Total\ Annual\ Cost\left(\frac{€}{yr}\right) = Annualized\ CAPEX\left(\frac{€}{yr}\right) + Annual\ OPEX\left(\frac{€}{yr}\right) \quad (13)$$

$$CO_2 captured\ cost\left(\frac{€}{t\ CO_2}\right) = \frac{Total\ Annual\ Cost\ (TAC)\left(\frac{€}{yr}\right)}{Mass\ of CO_2\ captured\left(\frac{t}{yr}\right)} \quad (14)$$

Where *n* represents operational years and *r* is discount/interest rate for a 2-year construction period and 23 years of operations (Aromada et al., 2020a). The economic assumptions used for estimating the capital cost are given in Table 9.

3.4. Operating and maintenance costs (O&M) and assumptions

To evaluate and compare the effects of the capital costs of the different methods on the total annual cost and CO_2 capture cost, operating cost was estimated. The fixed operating cost is assumed to consist of merely labour and maintenance costs. It is assumed that only six operators and one engineer (supervisor) are needed together with other workers from the main process plant. The work team will be much more

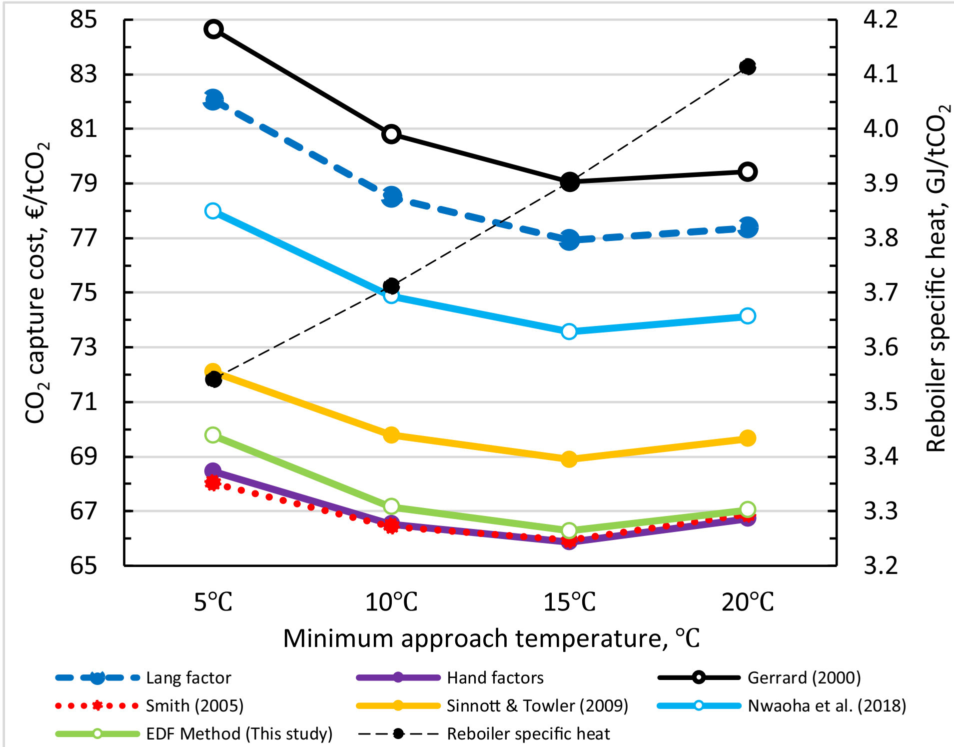

Fig. 15. Comparison of CO_2 capture costs estimated from the different factorial methods for CO_2 capture plant

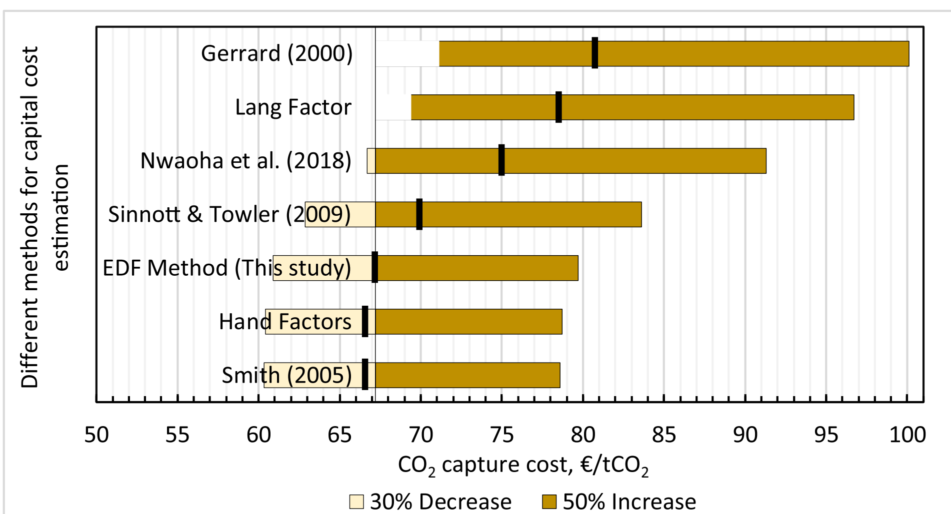

Fig. 16. Sensitivities of CAPEX estimate from the different factorial methods on CO_2 capture cost

for a stand-alone capture plant. Variable operating costs include cost of steam, electricity, process water, cooling water and solvent. The only difference in operating costs among the different methods is the maintenance cost which is derived from capital cost. We assumed the use of shell and tube heat exchangers for the lean/rich heat exchanger and coolers, and we accounted for the pressure drop. The economic assumptions used for the operating cost estimation are presented in Table 10.

4. Results and discussion

4.1. Simulation results

In Table 11, our simulation results are compared with published results of simulation of CO_2 capture processes from exhaust gas of natural gas fuelled power plants (Amrollahi et al., 2012; Dutta et al., 2017; Øi, 2007; N. Sipöcz et al., 2011; Nikolett Sipöcz and Tobiesen, 2012). The published results are for 85% and 90% CO_2 capture processes. The specific reboiler heat calculated in these publications ranges from 3.65 GJ/tCO_2 to 3.97 GJ/tCO_2. In this work, 3.54 GJ/tCO_2 and 3.71 GJ/tCO_2 were calculated for capture processes having lean/rich heat exchanger with minimum approach temperatures of 5°C and 10°C respectively. The simulated results in this work agree with the literature as is evident in Table 11. The rich loading in this work is only 0.03 higher than the other studies. Reference (Karimi et al., 2011) calculated 3.55 GJ/tCO_2 as the reboiler heat for a 90% CO_2 capture from a coal-fired power plant, with 5°C minimum approach temperature in the lean/rich heat exchanger. Even though the concentration of CO_2 (approximately 12

Table 14
Attributes/capabilities of the different factorial methods

Selected methods	ttributes/capabilities
Lang factor	Recognized that all plant types cannot have the same installation factor. Different installation factors for solid, fluid, and solid-fluid processing plants. Uniform installation factors, this is not realistic.
Hand factors	Considered that all equipment cannot have the same installation factor. Instruments and indirect cost are not included. Assigned different installation factors for each equipment type. Considered the material of equipment manufacturing.
Percentage of delivered-equipment cost (Gerrard, 2000)	Recognized that all plant types cannot have the same installation factor. Different installation factors for solid, fluid, and solid-fluid processing plants. Uniform installation factors, this is not realistic.
Percentage of delivered-equipment cost (Smith, 2005)	Recognized that all plant types cannot have the same installation factor. Different installation factor for solid and fluid processing plants. Assigned different material factors to different equipment. Uniform installation factors, this is not realistic. Applicable to only new plants.
Percentage of delivered-equipment cost (Sinnott & Towler, 2009)	Only considered the material of equipment manufacturing. Uniform installation factors, this is not realistic.
BEC (Nwaoha et al., 2018)	No information about the effect of material of construction on the installation factors. All equipment was in stainless steel. Uniform installation factors, this is not realistic.
EDF method	Recognizes that all plant types should not have the same installation factor. Different installation factors for solid and fluid processing plants. Accounts for different material of equipment manufacturing. Accounts different plant construction characteristic factors(PCCF) Installation factors are more detailed for both direct and indirect costs. Treats every piece of an equipment as a separate project. Each piece of equipment has its own installation factor based on the cost of the equipment. A very expensive piece of equipment has lower installation factor and a less expensive piece of equipment has high installation factor, this is realistic. The installation factors are regularly updated based on the economic realities like inflation and experience from full plant construction or modification projects. Emphasis on individual equipment for cost optimisation. The contribution of each equipment is known, so, attention can be given to the ones with the highest costs, to find ways to reduce the cost if possible. Ability to perform techno-economic assessment of new plants, new technologies, extension (modification) projects for an existing plant, small plants or packages, and large plants.

mole%) and the capture rate are higher, the results are almost the same.

The process specifications applied in this work are the same as in Øi (2007). The only difference is in the number of stages in the absorption and desorption columns. In this work, 15 and 10 equilibrium stages of absorption and desorption columns respectively were specified based on the Reference (Aromada and Øi, 2017). The equilibrium stages in the absorber and desorber in Øi (2007) are 10 and 6 respectively. The simulated heat requirements by the reboiler in this work is merely 1.6% higher than the value calculated in Øi (2007).

The heat consumption by the reboiler calculated in this study is only 0.8% less than the value in (Nikolett Sipöcz and Tobiesen, 2012). The simulation results obtained in this work are therefore satisfactory and reliable for practical techno-economic analysis of the amine-based CO_2 capture process.

4.2. Capital cost estimates from EDF method

Having validated the simulation results, capital cost estimation (total plant cost) of the CO_2 capture process was conducted, first by using the Enhanced Detailed Factor (EDF) method. Since the EDF method treats each equipment as a separate project, the installed cost of each equipment was estimated. The distribution of the TPC to the main plant equipment are presented in Fig. 6, and more details are given in Table 12. Fig. 4 illustrates that the EDF method is based on estimation of individual equipment installed cost, thereby revealing the influence of each equipment on the TPC. The absorber, lean/rich heat exchanger and compressors are the three most expensive equipment in this CO_2 capture process. The most expensive equipment can be given more attention, to optimise them. Most of the other factorial methods in literature apply a uniform factor on the sum of the equipment purchase cost. The cost contributions of each equipment are often concealed when estimates with these methods are presented.

Table 12 is not just meant to present the capital cost estimates, but it illustrates how the EDF method is implemented (See steps 1 – 12 in Section 2.5). Step 8 was not implemented here but in Section 4.6. Steps 5 and 4 are represented in columns 1 and 3 respectively. Step 6 is illustrated in columns 4 and 5, but in this work, it also includes column 6 because up to 2018, the installation factors of the EDF method were in Norwegian kroner, so currency conversion from Euro to Norwegian kroner (NOK) was necessary. Equipment costs in other currencies like US$ will still need to be converted to € in the updated list attached as Table C2 in Appendix C. Columns 7 and 8 demonstrate step 7 and 9 respectively. Column 8 is estimated using equation (6) or (7). So, the piping factor for each equipment needs to be obtained from the EDF list of installation factors. The equipment factor is always 1. Columns 9, 10 and 12 illustrate steps 10, 11 and 12 respectively. Since the equipment purchase costs were in Euros (€) and some equipment requires more than one unit, column 11 was added to show the total purchase cost of each equipment in Euros.

4.3. Comparison of capital costs from different methods

In order to illustrate how the installation factors and details considered in the different selected factorial methods affect the total plant cost (TPC), TPC was estimated from all the methods based on the same process and the same total equipment purchase costs. For the Lang factor method, the percentage of delivered-equipment cost in (Gerrard (2000) which is the same as in Peters et al. (2004), and the Bare Erected Cost (BEC) module method in Nwaoha et al. (2018), no other detail except the uniform installation factors are applied. The total plant costs are estimated by multiplying the total equipment costs directly with a uniform factor irrespective of the material of construction, type of equipment and cost of a unit of equipment.

For the percentage of delivered-equipment cost factorial method in Sinnott and Towler (2009) and Smith (2005), an extra detail of material of equipment construction is considered. The material factors in Smith (2005) are much higher than for any of the method that considers material of construction in this work (see Tables 4-6). Different material factors are also specified for different equipment. The Hand Factor method consists of two extra levels of details: each type of equipment is assigned an equipment factor and material of equipment construction is also considered and the final installation factor is estimated as done in Eq. (7) (Sinnott and Towler, 2009). The Hand factor method does not include instruments and indirect cost, and even in this work, they were not included to the Hand Factor method estimates. So, the estimates using Hand Factors should be higher to some extent, if the instrument and indirect costs are included. However, piping factors were also applied to estimate the final installation factors for equipment in SS while using Hand factors and the selected methods in (Sinnott and Towler, 2009; Smith, 2005). In the EDF method, the purchase (delivered) cost of each unit of equipment determines its installation factor and sub-factor (See Tables C1 and C2 in Appendix C).

The estimated TPC and the ratios between the total plant costs and total equipment costs using the different methods are compared in Fig. 5. The TPC estimates from the other three methods (Gerrard, 2000; Lang, 1948; Nwaoha et al., 2018) are much higher than the estimates from the four other methods that included more details. The capital cost estimate from the percentage of delivered-equipment cost factorial method in Gerrard (2000) gave the highest estimate. That is followed by Lang factor estimate. The TPC estimate using percentage of delivered-equipment cost factorial method in Smith (2005) has the lowest capital cost estimate, only approximately €1 million less than the capital cost estimate from the Hand Factors method. The very high material factors and details in Smith (2005) are responsible for the relatively very low estimates. This is because most of the equipment is assumed to be manufactured from stainless steel. Therefore, the total equipment costs in SS are required to be converted to their corresponding costs in CS (resulting in very low costs in CS) before applying the final equipment installation factors.

The capital cost estimates from the three methods based on a uniform factor are about 31% to 54% higher than the TPC estimate using the EDF method. The total plant cost estimated using percentage of equipment delivered cost factorial method in Sinnott and Towler (2009) is 10 % higher than TPC estimate from EDF method. While estimate of TPC from EDF method are 3% higher than the capital cost estimates using both Hand factors and percentage of equipment delivered cost factorial method in (Smith, 2005).

Further analysis was done for the four methods that included some details. An average overall final equipment installation factors was estimated for each method. The total equipment costs (TEC) were multiplied by the average installation factors to generate new capital costs. The results are compared with the original total plant costs in Fig. 6. The TPC estimates using average of the final installation factors in the EDF method increased by €58 million to €247 million. This is because, in the original capital cost estimate from EDF method, installation factors for the less and the least expensive equipment are relatively very high. That made the average final installation factor high. This is very significant which indicates that average factors do not represent reality as hinted by Smith (2005). Gerrard (2002) stated that detailed factors and sub-factors improve the accuracy of capital cost estimates. Ali et al. (2019) emphasized that the EDF method provides cost estimates with high accuracy at the early stage of projects. Hand factors and percentage of delivered-equipment cost factorial method in Smith (2005) also increased by €7 million and €14 million respectively. The increase in TPC in the case of Smith's percentage of delivered-equipment cost is far less than in the case of the EDF method. This is because of the very high material factors for equipment constructed in SS. In EDF method, 1.30 and 1.75 are the material factors used to convert equipment costs in SS machined equipment and in SS welded equipment to their corresponding costs in CS (see Table 4). While in the percentage of delivered-equipment cost in Smith (2005), the material factors to convert equipment costs in SS to their costs in CS are 2.9 for shell and tube heat exchanger, 3.2 for pressure vessels, and 3.4 for other equipment. These high material factors make the resulting costs of equipment in CS which is multiplied by installation factor(s) to obtain the TPC very low (see Table 6).

It is important to note that the ratio of total plant cost (TPC) to total equipment cost (TEC) is not the same as the installation factors for the four methods that included some details. This is because other sub-factors like piping sub-factor were included in the final installation factors for the equipment manufactured from SS. The more details considered in the factors the more reliable the capital cost estimates should be. Where the equipment required for a particular process plant are few, and if they are manufactured from the same material and with equipment costs that are relatively close, the average factor method estimates may be enough. However, where there are differences in material of construction and large difference in the cost of equipment, they may not give accurate or reliable capital cost estimates.

4.4. Impacts of different installation factors on equipment installed costs

The effects of equipment installation factors of the different methods on individual equipment with different purchase costs and material of construction are illustrated in this section. Three sets of equipment in the list of the equipment in Table 12 were selected for analysis based on their installed costs. They were categorized as most expensive in Fig. 7, expensive in Fig. 8 and less expensive in Fig. 9. These figures display both the total equipment cost (TEC) and the installed costs.

The method of percent of delivered-equipment cost in (Smith, 2005) has the lowest estimates for all the equipment in the three categories, except for the compressor and flue gas fan where the estimates using Hand factors are the lowest due to the very low installation factor of 2.5 for these equipment.

Generally, the most expensive (Fig. 7) and expensive (Fig. 8) equipment show almost the same trend as in Fig. 5, and also except for the compressors and flue gas fan for the Hand Factors which have a very low equipment type installation factor of 2.5. This is just a little above half of the uniform installation factor of the method of percent of delivered-equipment cost in (Gerrard, 2000) and Lang Factor for a fluid process. The equipment installed cost estimates of the EDF method, the Hand Factor method and percentage of delivered-equipment cost factorial methods in (Sinnott and Towler, 2009; Smith, 2005) that included some details are lower than those of the three methods based on uniform or average installation factors (Gerrard, 2000; Lang, 1948; Nwaoha et al., 2018).

The EDF method equipment installed cost estimates are some of the lowest for the most expensive and expensive equipment categories. However, the EDF method estimates are among the highest in the less expensive equipment category. These reveal the response of the EDF method installation factors to the cost of each piece of equipment, which is more realistic. That is why the EDF method is appropriate for both capital cost estimation of new plants and modification projects (concept screening and study estimates). This is an important advantage of the method. Anyone irrespective of experience can use the EDF method to obtain very good capital cost estimates. As new technologies and innovations in carbon capture technologies continue to emerge, they will require techno-economic assessments.

4.5. Overview of installation factors of different methods on each piece of equipment

The Hand installation factors and the installation factors of percentage of delivered equipment cost in Sinnott and Towler (2009) and Smith (2005) are compared with the EDF method installation factors both in CS and in SS for all the equipment as shown in Figs. 10-12. For both the EDF method and the Hand Factors scheme, the installation factors can straightforwardly be applied on each piece of equipment. In the case of percentage of delivered-equipment cost in Sinnott and Towler (2009) and Smith (2005), the uniform installation factor is applied on each piece of equipment in CS. For equipment in SS, the necessary conversion using individual equipment material factor in Smith (2005) and general material factor in Sinnott and Towler (2009), and average piping factor were implemented for each equipment.

The different installation factors for all the equipment in each method are linked with lines to clearly distinguish them. The upper lines represent the equipment installation factor for each piece of equipment in SS, and the lower line is for each piece of equipment in CS. The overlapped installation factors indicate where the equipment is manufactured in CS. In Fig. 10, both lines/trends in Hand Factors show the response of each piece of equipment to the individual equipment installation factors. In the EDF method, the installation factors respond to the cost of each piece or unit of an equipment.

In Fig. 11, the line of installation factors for equipment in CS for percentage of delivered equipment costs in Smith (2005) are in straight line, which indicates a uniform or overall installation factor. For each piece of equipment in SS, there are differences in the final installation factors, which illustrates that there are different material factors for different equipment. It can also be observed that for this method, the installation factors for equipment in SS are higher for expensive equipment (like absorber, lean/rich heat exchanger and DCC unit) than for those of EDF method. They are less than those for EDF method for SS equipment that are less expensive like the intercoolers. The installation factors in SS in this method and EDF method overlap for the five separators.

Sinnott and Towler (2009) in Fig. 12 shows a uniform installation factor for equipment in both CS and SS for percentage of delivered equipment cost as evident by the straight lines. This is because the same average factor in CS, the same material factor and the same piping factor are applied. Therefore, their total plant cost estimate is higher than estimates from the EDF method, Hand Factors and percentage of delivered-equipment cost in Smith (2005). The only improvement in the method is recognition of material of equipment construction.

These figures indicate that the equipment installation factors in the EDF method respond better to equipment costs, which is more realistic (Smith, 2005). The EDF method ensures improved capital cost estimates and offers the advantage of application for capital cost estimation for both new plants and modification projects.

4.6. EDF method plant construction characteristic factors (PCCF)

To account for the uniqueness of a construction project, we have introduced "plant construction characteristic factors (PCCF)" (See Table 2). Therefore, the EDF method presented in this work makes use of both installation factors/subfactors (Tables C1 and C2 in Appendix C) and plant construction characteristic factors. It is important as the conditions one will meet in different projects or at different locations due to weather, site and even availability of structures or instrument may be different.

A study of the effect of the PCCF in respect of civil engineering works, structures and building subfactor (direct cost and engineering cost) was conducted, and the results are presented in Fig. 13. For situations where no building is required, where the installed equipment is open on ground or open in a structure, the base case's total plant cost will decline by 2.3%, 1.8% or 0.6% respectively. Situations that need insulated closed structure(s) or where more than the normal ground preparation with piling is required, the effect is 2% or 5% increase respectively in the total plant cost. These are significant since the total plant cost is about €190 million. These extra factors enable EDF method to give capital cost estimates adapted to different situations.

4.7. Impacts of the different capital cost estimation methods on economic performance

To obtain different capital cost estimates for each method, analyses were conducted for four different CO_2 capture plant scenarios. The only difference in the four capture plant scenarios is differences in the minimum approach temperature (ΔT_{min}) of the lean/rich heat exchanger. The first, second, third and fourth scenarios have a lean/rich heat exchanger with a ΔT_{min} of 5°C, 10°C, 15°C and 20°C respectively. The capital cost of a solvent-based CO_2 capture plant varies with the ΔT_{min} of the lean/rich heat exchanger of the process. The lower the ΔT_{min}, the higher the capital cost; the cost of the heat exchanger network doubles by reducing the ΔT_{min} from 10°C to 5°C (Aromada et al., 2020b; Eimer, 2014; Karimi et al., 2011). And that has a substantial impact on the total plant cost.

Fig. 14 presents the capital cost estimates from the different methods. The EDF capital cost estimates are close to the other two methods that included some amount of details. That is Hand Factors that have specific equipment type installation factors and consider material of construction; and the percentage of delivered-equipment cost in Smith (2005), where different material factors are specified for different equipment. The lower the capital cost (the higher the ΔT_{min}) the closer the capital cost estimates of these three methods. In fact, for the ΔT_{min} of 5°C, 10°C, 15°C and 20°C investigated, Hand Factors capital cost estimates are 3.6%, 2.5%, 1.8% and 1.4% respectively less than the estimates of the EDF method. In the case of Smith (2005), they are 5.1%, 2.9%, 1.5% and 0.7% respectively less than the TPC estimates using EDF method.

On the other hand, the four other methods maintained approximately the same gap between each other. In the case of Sinnott and Towler (2009), for the ΔT_{min} of 5°C, 10°C, 15°C and 20°C examined, the TPC estimates are 9%, 11%, 11% and 12% respectively more than EDF method estimates. The TPC in case of Nwaoha et al. (2018) are 30%, 31%, 32% and 32% respectively more than the estimates using the EDF method. Lang Factor capital cost estimates exceed the estimates of the EDF method by 44%, 45%, 46% and 46% respectively. While in Gerrard (2000), the estimates are 53%, 54%, 55% and 56% respectively more than EDF method estimates. These illustrate that the changes in some major equipment costs, which led to reduction of TPC due to increase in ΔT_{min} from 5°C to 20°C do not have any significant effect on the equipment installation factors. Nevertheless, these four methods do not show any considerable response beyond merely reducing the total capital cost at a constant rate because they are based on a uniform or an average overall plant's installation factors.

The fixed operating costs and variable operating cost were also estimated to assess the effects of the different methods on the carbon capture cost. The resulting CO_2 capture costs from the different methods range from €68 – €85/tCO_2, €66 – €81/tCO_2, €66 – €74/tCO_2 and €67 – €79/tCO_2 for the 5°C, 10°C, 15°C and 20°C ΔT_{min} scenarios respectively, as can be observed in Table 13 and Fig. 15. The book of Gerrard (Gerrard, 2000) presented many methods. For readers to be sure of the method in (Gerrard et al., 2000) examined in this work, [%DEQ] is added to the description of the methods based on percentage of delivered-equipment costs in Table 13 and the tables attached in the Appendix. [BEC] is added to Nwaoha et al. (2018) method to show that it is based on Bare Erected Cost scheme. The method of percentage of delivered-equipment cost in Smith (2005) estimated the lowest CO_2 capture costs in the 5°C and 10°C ΔT_{min} scenarios at which the capital costs are higher. The Hand factors method estimated the least CO_2 capture costs in the 15°C and 20°C ΔT_{min} scenarios. All the methods estimated their cost optimum to be the plant scenario with ΔT_{min} of 15°C as it can be seen in Fig. 15. The specific heat consumption by the reboiler at the cost optimum is 3.9 GJ/tCO_2. In recent studies, a minimum approach temperature of 15°C was also estimated as the cost optimum in a process of CO_2 capture from cement plant's flue gas (Aromada et al., 2020b).

The range of the CO_2 capture costs estimated by the different methods in each ΔT_{min} scenario is significant. The method employed for estimation of capital cost will have a large impact on the economic analysis results obtained. This is also important when making comparison with other studies. The total annual costs and CO_2 capture costs estimated using the EDF methods are closest to the estimates of Hand Factors and the method of percentage of delivered equipment cost in Smith (2005). The estimates of the three methods that included more details, which are the EDF method, Hand Factors and method of percentage of delivered equipment cost in Smith (2005) are close. The closeness increases as the minimum approach temperature decreases. The other four methods maintain approximately the same gaps among them across the four ΔT_{min} investigated. This is because the equipment installation factors of Lang Factor, percentage of delivered equipment cost method and BEC module method are usually fixed except when some details are introduced as in Smith (2005) where material factors depend on equipment type, and in the Hand Factor method where the installation factors depend on the type of equipment. The EDF installation factors respond to the cost of each piece of main plant item, therefore, accuracy of estimates will likely be higher.

According to Carbon Capture and Storage Association (2011), the power industry's carbon capture cost range is €60/tCO_2 – €90/tCO_2. Specifically, Rubin et al. (2015) put this range for CO_2 capture from natural gas combined-cycle (NGCC) power plant's exhaust gas in 2013 constant dollar at US$48/t$CO_2$ – US$111/t$CO_2$ (€45/tCO_2 – €104/tCO_2, adjusted to 2018 and converted to Euros). They stated that the representative value in 2013 is US$74/t$CO_2$ (€69/tCO_2, adjusted to 2018 and converted to Euros). As can be seen in Table 13, the minimum CO_2 capture cost estimated in this work is €66/tCO_2 by Smith (2005), Hand Factors and EDF method, which is for the 15°C ΔT_{min} plant scenario. While the maximum capture cost is €85/tCO_2 by Gerrard (2000), and it is for the 5°C ΔT_{min} plant scenario. Even though there is a wide difference between €66/tCO_2 – €85/tCO_2, the values are within ranges in literature. These wide differences in capture cost reflect the dissimilarities in the method applied for cost estimation, the scope of the analyses, and the underlying assumptions (Ali et al., 2019). This work is concerned with the methods used for cost estimation, and the results so far have revealed that differences in the method used for cost estimation, due to the installation factors could also cause a wide difference among estimates. Yet, cost estimates from the more detailed methods, which have installation factors that depend on the cost of the equipment or on the type of equipment, and material factors that either depend on mode of construction (welded or machined) or on the type of equipment are relatively close. The cost estimates from the methods that are mainly based on application of a uniform installation factor on all main plant equipment vary much. This difference in the cost estimates is vital when assessing the feasibility of a project or technology, and it emphasizes the significance of guaranteeing the consistency and transparency in cost estimations (Ali et al., 2019).

4.8. Sensitivity of CO_2 capture costs to CAPEX from the different methods

Further sensitivities of the capital cost estimates from the different methods were also conducted to evaluate their impacts on the CO_2 capture cost estimated by each method. The sensitivity estimates where compared with the EDF method's original CO_2 capture cost estimate from the base case plant, with a lean/rich heat exchanger which have a ΔT_{min} of 10°C. Since the seven methods investigated in this work fall mainly under the class 4, though the Lang Factor is under Class 5 of the A.A.C.E. classification, the error margin for Class 4 is -30% and +50% Bredehoeft et al. (2020). Therefore, it is justifiable to base the sensitivity analysis on a probable range of -30/+50%.

In case of 30% decrease in capital cost, the CO_2 capture cost estimated using the EDF method will decrease from of €67/tCO_2 to about €60/tCO_2 as can be observed in Fig. 16. A decrease of 30% in the capital cost estimates of the method of percentage of delivered-equipment cost in Gerrard (2000) and Lang Factor will still give a CO_2 capture cost above the original estimate of EDF method. For the BEC module method in Nwaoha et al. (2018), a 30% decrease in capital cost results to €2/tCO_2 less than the original EDF method capture cost. In the case of Sinnott and Towler (2009), it is around €6/tCO_2 less than the original EDF method estimate. The Hand Factors and Smith (2005) show an €8/tCO_2 less than the original CO_2 capture cost from the EDF method, in case of 30% decrease in capital cost.

On the other hand, if a 50% increase in capital cost occurs, the EDF method CO_2 capture cost will increase to almost €80/tCO_2, which is about €13/tCO_2 increase. The capture cost estimates of the other six methods will be about €12/tCO_2, €12/tCO_2, €17/tCO_2, €24/tCO_2, €30/tCO_2, and €33/tCO_2 above the original estimate by EDF method. These also reveal that the estimates from the methods based on a uniform installation factor vary much due to the different average values assumed. Even though the uniform installation factor in Smith (2005) is 4.8, which is very close but slightly higher than the Lang Factor, introduction of equipment types specific material factor made its estimates far less than those of Lang Factor and even estimates using Sinnott and Towler (2009) and Nwaoha et al. (2018). The original capture cost of each method is signified by a short black thick vertical line in Fig. 16. In all the estimates and sensitivity analysis in this work, the estimates of the EDF method, the Hand Factor method and Smith (2005) are close which indicate that methods that involve more details may give estimates that are relatively close.

4.9. Summary attributes or capabilities of each method

The general attributes or capabilities of each method are summarised in Table 14.

5. Conclusion

This work highlighted the capabilities and suitability of the EDF method for initial capital cost estimation of different types of projects, and different plant construction characteristic situations. The effects of the installation factors of different factorial cost estimation methods on the capital cost (total plant cost), and on the overall capture cost of an amine-based CO_2 capture plant were evaluated. The EDF method estimates are relatively close to the estimates using percentage of delivered equipment cost in Smith (2005) and Hand Factors. The estimates of the other methods that are mainly founded on uniform or overall plant's average installation factor were much higher than estimates from the EDF method, Hand Factor method and percentage of delivered equipment cost in Smith (2005). This indicates that applying a uniform installation factor on all main plant items will likely lead to errors. A very costly equipment could be over-estimated and less expensive equipment could be underestimated. In addition, disregarding to properly correct equipment installation factors for materials of equipment construction is one of the main causes of error with the factorial capital cost estimation methods.

The EDF method treats each equipment as a separate project and highlights equipment that requires cost optimisation. The subfactors and total installation factor of each piece of equipment depends on the cost of the equipment. The higher the cost of any piece of equipment, the lower the installation factor and vice versa. This is more reasonable than applying a uniform installation factor on all main plant equipment irrespective of the cost of the equipment. That is why the EDF method is also suitable for capital cost estimation in modification projects.

A special set of factors referred to as plant construction characteristic factors (PCCF) were also introduced, to account for projects with different characteristic situations, for example, adverse weather condition, reuse of already owned main plant item, ground preparation which involves piling or other situations. The EDF method is regularly updated to reflect current realities. Anyone irrespective of experience can use the EDF method to obtain good capital cost estimates.

In a base case plant scenario, a CO_2 capture cost of €67/tCO_2 was estimated using the EDF method. Hand Factors also estimated of €67/tCO_2, while of €66/tCO_2 was estimated using the percentage of delivered equipment cost in Smith (2005). The base case estimate using Lang Factor is €79/tCO_2. The percentage of delivered equipment cost method in Gerrard (2000) and Peters et al. (2004) estimated the highest capital cost and a capture cost of €81/tCO_2 in the base case scenario.

All the methods calculated the cost optimum ΔT_{min} in the lean/rich heat exchanger to be 15°C. However, the EDF method, Smith's percentage of delivered equipment cost and Hand Factorial method estimated approximately the same carbon capture cost for the cost optimum ΔT_{min} to be €66/tCO_2. The other four methods estimated it to be €69–79/tCO_2.

The EDF method's layout makes the estimates more transparent, and it becomes easier to communicate between the cost estimator and the process developer. That is, this method is very good during the process development because the process engineer can see the effect of his choices very quickly.

Author Contributions

Conceptualization, methodology, investigation, formal analysis, writing—original draft preparation, writing—review and editing, S.A. A.; methodology, supervision, writing—review and editing, N.H.E.; supervision, resources, writing—review and editing, L.E.-Ø.

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Declaration of Competing Interest

The authors declare no conflict of interest.

Appendix A

Fig. A1

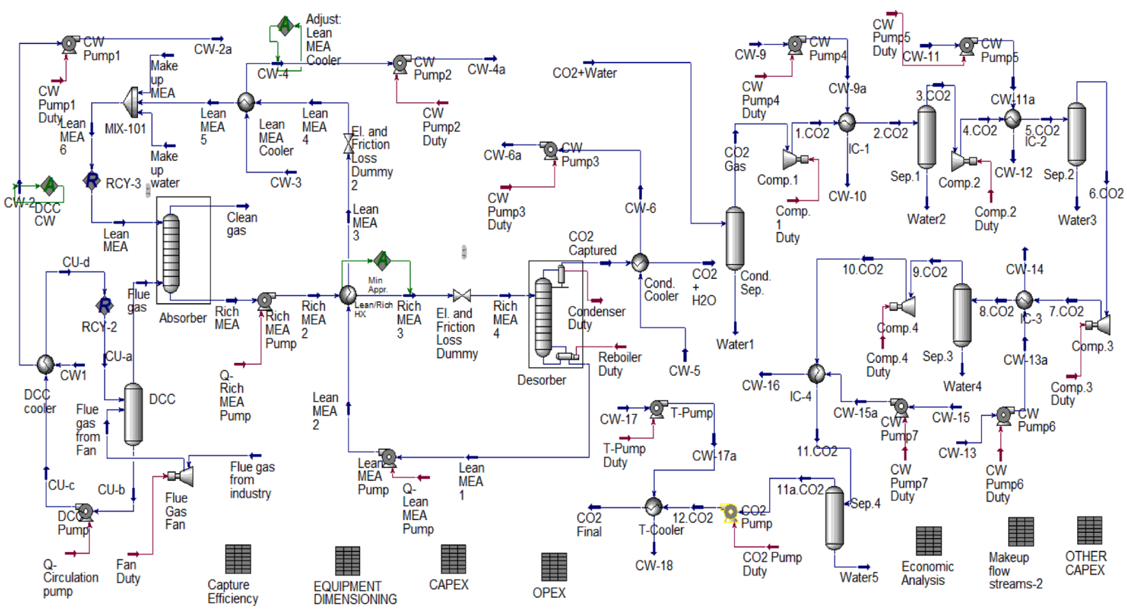

Fig. A1. Aspen HYSYS process flow diagram of the CO_2 capture plant

Appendix B

Table B1-B4

Table B1
Total plant costs (TPC)/CAPEX from different methods, having fixed tube-sheets shell and tube heat exchanger as the lean/rich heat exchanger with a designed ΔT_{min} of 5 °C

Equipment	Mat.	Equip. size/ unit Diameter	Height	Nos.	Total plant cost (TPC) form different methods Equip. Cost	EDF method	Hand factors	Smith (2005) [% DEQ]	Sinnott & Towler (2009) [% DEQ]	Nwaoha et al. (2018) [BEC]	Lang factor	Gerrard (2000) [% DEQ]
		m	*m*		M€							
DCC unit shell	SS	13	15	1	2.55	8.02	8.91	6.81	8.91	10.90	12.10	12.86
DCC-unit packing	SS	13	4	1	2.02	6.34	7.05	5.39	7.05	8.62	9.57	10.17
Absorber shell	SS	12	40	2	4.71	24.55	32.93	25.16	32.93	40.26	44.69	47.52
Absorber packing	SS	12	15	2	5.54	28.86	38.70	29.58	38.70	47.32	52.53	55.86
Desorber shell	SS	7	22	1	1.37	4.30	4.78	3.65	4.78	5.85	6.49	6.90

(*continued on next page*)

Table B1 (*continued*)

Desorber packing	SS	7	10	1	1.25	3.94	4.38	3.34	4.38	5.35	5.94	6.31
Condensate separator	SS	2.8	8.5	1	0.16	0.79	0.56	0.43	0.56	0.69	0.77	0.81
Separator 1	SS	2.2	6.7	1	0.11	0.53	0.38	0.29	0.38	0.46	0.51	0.54
Separator 2	SS	1.8	5.4	1	0.12	0.61	0.43	0.33	0.43	0.53	0.59	0.63
Separator 3	SS	1.4	4.2	1	0.13	0.64	0.46	0.35	0.46	0.56	0.62	0.66
Separator 4	SS	1	3.1	1	0.16	0.76	0.54	0.42	0.54	0.66	0.74	0.78
	Heat transfer Area, m^2											
DCC cooler	SS	697		2	0.36	2.46	2.22	1.97	2.49	3.04	3.38	3.59
Lean/rich HX	SS	991		34	0.56	66.00	59.42	52.95	66.78	81.65	90.64	96.37
Reboiler	SS	828		3	0.50	5.20	4.68	4.17	5.26	6.43	7.14	7.59
Condenser	SS	212		1	0.13	0.64	0.41	0.36	0.46	0.56	0.62	0.66
Lean MEA cooler	SS	541		2	0.32	2.65	1.96	1.75	2.21	2.70	2.99	3.18
Intercooler 1	SS	91		1	0.06	0.38	0.19	0.17	0.22	0.27	0.30	0.31
Intercooler 2	SS	83		1	0.06	0.37	0.19	0.17	0.21	0.26	0.29	0.30
Intercooler 3	SS	86		1	0.06	0.39	0.20	0.18	0.22	0.27	0.30	0.32
Intercooler 4	SS	136		1	0.10	0.50	0.32	0.28	0.36	0.44	0.49	0.52
T-Cooler	SS	40		1	0.02	0.14	0.07	0.06	0.08	0.10	0.11	0.12
Condensate cooler	SS	861		1	0.43	1.50	1.35	1.20	1.51	1.85	2.06	2.19
	Flow, m^3/h	Power, kW										
Flue gas fan	CS	1 234 992	3 991	2	1.39	12.31	6.93	13.30	11.09	11.84	13.14	13.97
Compressor 1	CS	46 828	3 000	1	4.07	14.62	10.18	19.54	16.29	17.39	19.30	20.52
Compressor 2	CS	18 422	2 909	1	2.37	8.51	5.92	11.37	9.48	10.12	11.23	11.94
Compressor 3	CS	6 630	2 789	1	1.51	5.42	3.77	7.25	6.04	6.45	7.16	7.61
Compressor 4	CS	2 154	2 506	1	1.78	6.38	4.44	8.53	7.11	7.59	8.42	8.96
	Flow, L/s	Power, kW										
DCC pump	SS	1 823	464	1	0.85	3.20	2.99	2.23	2.99	3.65	4.05	4.31
Rich pump	SS	609	226	1	0.20	0.99	0.68	0.51	0.68	0.84	0.93	0.99
Lean pump	SS	629	252	1	0.23	1.16	0.80	0.59	0.80	0.97	1.08	1.15
CW pump 1	CS	647	8.4	1	0.11	0.67	0.44	0.53	0.44	0.47	0.52	0.55
CW pump 2	CS	902	12.1	1	0.10	0.63	0.41	0.50	0.41	0.44	0.49	0.52
CW pump 3	CS	596	8	1	0.12	0.75	0.49	0.59	0.49	0.53	0.59	0.62
CW pump 4	CS	100	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 5	CS	95	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 6	CS	100	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 7	CS	148	2	1	0.03	0.24	0.11	0.13	0.11	0.11	0.12	0.13
T-pump	CS	22	0.3	1	0.01	0.14	0.04	0.05	0.04	0.04	0.05	0.05
CO_2 pump	SS	105	537	1	0.16	0.83	0.57	0.43	0.57	0.70	0.77	0.82
Total plant cost (TPC)						**215.90**	**208.12**	**204.82**	**235.66**	**280.11**	**310.94**	**330.62**

Table B2
Total plant costs (TPC)/CAPEX from different methods, having fixed tube-sheets shell and tube heat exchanger as the lean/rich heat exchanger with a designed ΔT_{min} of 10 °C

Equipment	Mat.	Equip. size/ unit		Nos.	Total plant cost (TPC) form different methods							
		Diameter	Height		Equip. Cost	EDF method	Hand factors	Smith (2005) [% DEQ]	Sinnott & Towler (2009) [%DEQ]	Nwaoha et al. (2018) [BEC]	Lang factor	Gerrard (2000) [% DEQ]
		m	*m*		M€							
DCC unit shell	SS	13	15	1	2.55	8.02	8.91	6.81	8.91	10.90	12.10	12.86
DCC-unit packing	SS	13	4	1	2.02	6.34	7.05	5.39	7.05	8.62	9.57	10.17
Absorber shell	SS	12	40	2	4.71	24.55	32.93	25.16	32.93	40.26	44.69	47.52
Absorber packing	SS	12	15	2	5.54	28.86	38.70	29.58	38.70	47.32	52.53	55.86
Desorber shell	SS	7.2	22	1	1.40	4.41	4.90	3.75	4.90	5.99	6.65	7.07
Desorber packing	SS	7.2	10	1	1.31	4.11	4.57	3.49	4.57	5.59	6.20	6.60
Condensate separator	SS	2.8	8.5	1	0.16	0.79	0.56	0.43	0.56	0.69	0.76	0.81
Separator 1	SS	2.2	6.7	1	0.11	0.53	0.38	0.29	0.38	0.46	0.51	0.54
Separator 2	SS	1.8	5.4	1	0.12	0.61	0.43	0.33	0.43	0.53	0.59	0.63
Separator 3	SS	1.4	4.2	1	0.13	0.64	0.46	0.35	0.46	0.56	0.62	0.66
Separator 4	SS	1	3.1	1	0.16	0.76	0.54	0.42	0.54	0.66	0.74	0.78
	Heat transfer Area, m^2											
DCC cooler	SS	697		2	0.36	2.46	2.22	1.97	2.49	3.04	3.38	3.59
Lean/rich HX	SS	997		20	0.56	38.95	35.07	31.25	39.41	48.19	53.50	56.88
Reboiler	SS	860		3	0.52	5.36	4.82	4.30	5.42	6.63	7.36	7.82
Condenser	SS	204		1	0.13	0.62	0.39	0.35	0.44	0.54	0.60	0.64
Lean MEA cooler	SS	716		2	0.37	2.57	2.31	2.06	2.60	3.17	3.52	3.75
Intercooler 1	SS	91		1	0.06	0.38	0.19	0.17	0.22	0.27	0.30	0.31
Intercooler 2	SS	83		1	0.06	0.37	0.19	0.17	0.21	0.26	0.29	0.30
Intercooler 3	SS	86		1	0.06	0.39	0.20	0.18	0.22	0.27	0.30	0.32
Intercooler 4	SS	136		1	0.10	0.51	0.32	0.29	0.36	0.44	0.49	0.52
T-Cooler	SS	40		1	0.02	0.14	0.07	0.06	0.08	0.10	0.11	0.12
Condensate cooler	SS	742		1	0.39	1.33	1.20	1.07	1.35	1.65	1.83	1.94
	Flow, m^3/h		Power, *kW*									
Flue gas fan	CS	1234 992	3 991	2	1.39	12.31	6.93	13.30	11.09	11.84	13.14	13.97
Compressor 1	CS	46 790	2 998	1	4.07	14.62	10.18	19.54	16.29	17.39	19.30	20.52
Compressor 2	CS	18 407	2 907	1	2.37	8.51	5.92	11.37	9.48	10.12	11.23	11.94
Compressor 3	CS	6 625	2 787	1	1.51	5.42	3.77	7.25	6.04	6.45	7.16	7.61
Compressor 4	CS	2 152	2 504	1	1.78	6.38	4.44	8.53	7.11	7.59	8.42	8.96
	Flow, *L/s*		Power, *kW*									
DCC pump	SS	1 823	464	1	0.85	3.20	2.99	2.23	2.99	3.65	4.05	4.31
Rich pump	SS	614	228	1	0.20	1.00	0.69	0.51	0.69	0.84	0.93	0.99
Lean pump	SS	636	254	1	0.23	1.17	0.80	0.60	0.80	0.98	1.09	1.16
CW pump 1	CS	647	8.4	1	0.11	0.67	0.44	0.53	0.44	0.47	0.52	0.55
CW pump 2	CS	902	12.1	1	0.17	1.05	0.69	0.83	0.69	0.74	0.82	0.87
CW pump 3	CS	596	8	1	0.10	0.61	0.40	0.48	0.40	0.42	0.47	0.50
CW pump 4	CS	100	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 5	CS	95	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 6	CS	100	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 7	CS	148	2	1	0.03	0.24	0.10	0.13	0.10	0.11	0.12	0.13
T-pump	CS	22	0.3	1	0.01	0.14	0.04	0.05	0.04	0.04	0.05	0.05
CO_2 pump	SS	105	537	1	0.16	0.83	0.57	0.43	0.57	0.70	0.77	0.82
Total plant cost (TPC)						**189.32**	**184.60**	**183.88**	**209.17**	**247.70**	**274.96**	**292.36**

Table B3
Total plant costs (TPC)/CAPEX from different methods, having fixed tube-sheets shell and tube heat exchanger as the lean/rich heat exchanger with a designed ΔT_{min} of 15 °C

Equipment	Mat.	Equip. size/ unit			Total plant cost (TPC) form different methods							
		Diameter	Height	Nos.	Equip. Cost	EDF method	Hand factors	Smith (2005) [% DEQ]	Sinnott & Towler (2009) [%DEQ]	Nwaoha et al. (2018) [BEC]	Lang factor	Gerrard (2000) [% DEQ]
		m	*m*		M€							
DCC unit shell	SS	13	15	1	2.55	8.02	8.91	6.81	8.91	10.90	12.10	12.86
DCC-unit packing	SS	13	4	1	2.02	6.34	7.05	5.39	7.05	8.62	9.57	10.17
Absorber shell	SS	12	40	2	4.71	24.55	32.93	25.16	32.93	40.26	44.69	47.52
Absorber packing	SS	12	15	2	5.54	28.86	38.70	29.58	38.70	47.32	52.53	55.86
Desorber shell	SS	7.4	22	1	1.54	4.83	5.36	4.10	5.36	6.56	7.28	7.74
Desorber packing	SS	7.4	10	1	1.37	4.32	4.80	3.67	4.80	5.87	6.51	6.93
Condensate separator	SS	2.8	8.5	1	0.16	0.79	0.56	0.43	0.56	0.69	0.77	0.81
Separator 1	SS	2.2	6.7	1	0.11	0.53	0.38	0.29	0.38	0.46	0.51	0.54
Separator 2	SS	1.8	5.4	1	0.12	0.61	0.43	0.33	0.43	0.53	0.59	0.63
Separator 3	SS	1.4	4.2	1	0.13	0.64	0.46	0.35	0.46	0.56	0.62	0.66
Separator 4	SS	1	3.1	1	0.16	0.76	0.54	0.42	0.54	0.66	0.74	0.78
	Heat transfer Area, m^2											
DCC cooler	SS	697		2	0.36	2.46	2.22	1.97	2.49	3.05	3.38	3.59
Lean/rich HX	SS	995		12	0.56	23.35	21.03	18.73	23.63	28.89	32.07	34.10
Reboiler	SS	894		3	0.53	5.49	4.94	4.41	5.56	6.79	7.54	8.02
Condenser	SS	197		1	0.12	0.61	0.39	0.34	0.43	0.53	0.59	0.62
Lean MEA cooler	SS	943		2	0.47	3.24	2.92	2.60	3.28	4.01	4.45	4.74
Intercooler 1	SS	91		1	0.06	0.38	0.19	0.17	0.22	0.27	0.30	0.31
Intercooler 2	SS	83		1	0.06	0.37	0.19	0.17	0.21	0.26	0.29	0.30
Intercooler 3	SS	86		1	0.06	0.39	0.20	0.18	0.22	0.27	0.30	0.32
Intercooler 4	SS	136		1	0.10	0.51	0.32	0.29	0.36	0.44	0.49	0.52
T-Cooler	SS	40		1	0.02	0.14	0.07	0.06	0.08	0.10	0.11	0.12
Condensate cooler	SS	596		1	0.31	1.07	0.96	0.86	1.08	1.32	1.47	1.56
	Flow, m^3/h		Power, kW									
Flue gas fan	CS	1 234 992	3 991	2	1.39	12.31	6.93	13.30	11.09	11.84	13.14	13.97
Compressor 1	CS	46 790	2 996	1	4.07	14.62	10.18	19.54	16.29	17.39	19.30	20.52
Compressor 2	CS	18 407	2 905	1	2.37	8.51	5.92	11.37	9.48	10.12	11.23	11.94
Compressor 3	CS	6 625	2 785	1	1.51	5.42	3.77	7.25	6.04	6.45	7.16	7.61
Compressor 4	CS	2 152	2 502	1	1.78	6.38	4.44	8.53	7.11	7.59	8.42	8.96
	Flow, L/s		Power, kW									
DCC pump	SS	1 823	464	1	0.85	3.20	2.99	2.23	2.99	3.65	4.05	4.31
Rich pump	SS	609	227	1	0.20	0.99	0.68	0.51	0.68	0.84	0.93	0.99
Lean pump	SS	641	256	1	0.23	1.17	0.81	0.60	0.81	0.99	1.10	1.17
CW pump 1	CS	647	8.4	1	0.11	0.67	0.44	0.53	0.44	0.47	0.52	0.55
CW pump 2	CS	902	12.1	1	0.17	1.05	0.69	0.83	0.69	0.74	0.82	0.87
CW pump 3	CS	596	8	1	0.07	0.52	0.29	0.35	0.29	0.31	0.35	0.37
CW pump 4	CS	100	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 5	CS	95	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 6	CS	100	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 7	CS	148	2	1	0.03	0.24	0.11	0.13	0.11	0.11	0.13	0.13
T-pump	CS	22	0.3	1	0.01	0.14	0.04	0.05	0.04	0.04	0.05	0.05
CO_2 pump	SS	105	537	1	0.16	0.83	0.57	0.43	0.57	0.70	0.77	0.82
Total plant cost (TPC)						**174.80**	**171.63**	**172.20**	**194.51**	**229.80**	**255.09**	**271.23**

Table B4
Total plant costs (TPC)/CAPEX from different methods, having fixed tube-sheets shell and tube heat exchanger as the lean/rich heat exchanger with a designed ΔT_{min} of 20 °C

Equipment	Mat.	Equip. size/ unit		Nos.	Total plant cost (TPC) form different methods							
		Diameter	Height		Equip. Cost	EDF method	Hand factors	Smith (2005) [%DEQ]	Sinnott & Towler (2009) [%DEQ]	Nwaoha et al. (2018)	Lang factor	Gerrard (2000) [%DEQ]
		M	*m*		M€							
DCC unit shell	SS	13	15	1	2.55	8.02	8.91	6.81	8.91	10.90	12.10	12.86
DCC-unit packing	SS	13	4	1	2.02	6.34	7.05	5.39	7.05	8.62	9.57	10.17
Absorber shell	SS	12	40	2	4.71	24.55	32.93	25.16	32.93	40.26	44.69	47.52
Absorber packing	SS	12	15	2	5.54	28.86	38.70	29.58	38.70	47.32	52.53	55.86
Desorber shell	SS	7.4	22	1	1.58	4.95	5.51	4.21	5.51	6.74	7.48	7.95
Desorber packing	SS	7.4	10	1	1.44	4.54	5.04	3.85	5.04	6.17	6.85	7.28
Condensate separator	SS	2.8	8.5	1	0.16	0.79	0.56	0.43	0.56	0.69	0.77	0.81
Separator 1	SS	2.2	6.7	1	0.11	0.53	0.38	0.29	0.38	0.46	0.51	0.54
Separator 2	SS	1.8	5.4	1	0.12	0.61	0.43	0.33	0.43	0.53	0.59	0.63
Separator 3	SS	1.4	4.2	1	0.13	0.64	0.46	0.35	0.46	0.56	0.62	0.66
Separator 4	SS	1	3.1	1	0.16	0.76	0.54	0.42	0.54	0.66	0.74	0.78
	Heat transfer Area per unit, m^2											
DCC cooler	SS	697		2	0.36	2.46	2.22	1.97	2.49	3.04	3.38	3.59
Lean/rich HX	SS	995		8	0.57	15.61	14.06	12.53	15.80	19.32	21.44	22.80
Reboiler	SS	894		3	0.55	5.69	5.13	4.57	5.76	7.04	7.82	8.31
Condenser	SS	197		1	0.12	0.58	0.37	0.33	0.41	0.51	0.56	0.60
Lean MEA cooler	SS	943		3	0.36	3.69	3.32	2.96	3.74	4.57	5.07	5.39
Intercooler 1	SS	91		1	0.06	0.38	0.19	0.17	0.22	0.27	0.30	0.31
Intercooler 2	SS	83		1	0.06	0.37	0.19	0.17	0.21	0.26	0.29	0.30
Intercooler 3	SS	86		1	0.06	0.39	0.20	0.18	0.22	0.27	0.30	0.32
Intercooler 4	SS	136		1	0.10	0.51	0.32	0.29	0.36	0.44	0.49	0.52
T-Cooler	SS	40		1	0.02	0.14	0.07	0.06	0.08	0.10	0.11	0.12
Condensate cooler	SS	596		1	0.27	0.93	0.84	0.75	0.94	1.15	1.28	1.36
	Flow, m^3/h		Power, *kW*									
Flue gas fan	CS	1 234 992	3 991	2	1.39	12.31	6.93	13.30	11.09	11.84	13.14	13.97
Compressor 1	CS	46 790	2 996	1	4.07	14.62	10.18	19.54	16.29	17.39	19.30	20.52
Compressor 2	CS	18 407	2 905	1	2.37	8.51	5.92	11.37	9.48	10.12	11.23	11.94
Compressor 3	CS	6 625	2 785	1	1.51	5.42	3.77	7.25	6.04	6.45	7.16	7.61
Compressor 4	CS	2 152	2 502	1	1.78	6.38	4.44	8.53	7.11	7.59	8.42	8.96
	Flow, *L/s*		Power, *kW*									
DCC pump	SS	1 823	464	1	0.85	3.20	2.99	2.23	2.99	3.65	4.05	4.31
Rich pump	SS	609	227	1	0.19	0.99	0.68	0.51	0.68	0.83	0.92	0.98
Lean pump	SS	641	256	1	0.23	1.17	0.80	0.60	0.80	0.98	1.09	1.16
CW pump 1	CS	647	8.4	1	0.11	0.67	0.44	0.53	0.44	0.47	0.52	0.55
CW pump 2	CS	902	12.1	1	0.17	1.05	0.69	0.83	0.69	0.74	0.82	0.87
CW pump 3	CS	596	8	1	0.07	0.52	0.29	0.35	0.29	0.31	0.35	0.37
CW pump 4	CS	100	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 5	CS	95	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 6	CS	100	1.3	1	0.02	0.16	0.07	0.08	0.07	0.08	0.08	0.09
CW pump 7	CS	148	2	1	0.03	0.24	0.11	0.13	0.11	0.11	0.13	0.13
T-pump	CS	22	0.3	1	0.01	0.14	0.04	0.05	0.04	0.04	0.05	0.05
CO_2 pump	SS	105	537	1	0.16	0.83	0.57	0.43	0.57	0.70	0.77	0.82
Total plant cost (TPC)						**167.88**	**165.49**	**166.68**	**187.56**	**221.30**	**245.66**	**261.20**

Appendix C

Tables C1-C2a

Table C1

Installation Factor Sheet for the period 2016–2018. Prepared by Nils Henrik Eldrup (USN and SINTEF Tel-Tek)

Cost of equipment in carbon steel (CS)	**Fluid**								**Solid**						
kNOK	**0–20**	**20–100**	**100–500**	**500–1000**	**1000–2000**	**2000–5000**	**5000–15000**	**>15000**	**0-20**	**20–100**	**100–500**	**500–1000**	**1000–2000**	**2000–5000**	**>5000**
Equipment, f_{equip}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Erection/Installation, $f_{erection}$	0.89	0.47	0.25	0.18	0.14	0.11	0.1	0.08	1.97	1.04	0.61	0.43	0.36	0.25	0.22
Piping, f_{piping}	3.56	1.92	1.12	0.83	0.65	0.48	0.41	0.29	0.72	0.39	0.22	0.17	0.13	0.1	0.09
Electric, f_{elec}	1.03	0.71	0.48	0.41	0.34	0.28	0.25	0.18	1.74	1.09	0.72	0.56	0.47	0.39	0.33
Instrument, f_{inst}	3.56	1.92	1.12	0.83	0.65	0.48	0.41	0.29	1.41	0.77	0.46	0.33	0.27	0.18	0.15
Civil, f_{civil}	0.55	0.36	0.25	0.2	0.17	0.14	0.13	0.09	1.26	0.75	0.48	0.37	0.29	0.24	0.2
Steel & Concrete, $f_{S\&C}$	1.79	1.17	0.79	0.64	0.55	0.43	0.39	0.28	2.5	1.55	1.02	0.79	0.66	0.52	0.47
Insulation, $f_{insulation}$	0.67	0.34	0.18	0.14	0.11	0.09	0.05	0.04	0.67	0.34	0.18	0.14	0.11	0.09	0.05
Direct Cost, f_{direct}	**13.04**	**7.88**	**5.19**	**4.21**	**3.6**	**3.02**	**2.74**	**2.24**	**11.27**	**6.94**	**4.68**	**3.78**	**3.29**	**2.78**	**2.51**
Engineering Process, $f_{engg.process}$	1.23	0.43	0.24	0.18	0.15	0.13	0.11	0.09	1.23	0.43	0.24	0.18	0.15	0.13	0.11
Engineering Mechanical, $f_{engg.mech}$	0.98	0.24	0.1	0.05	0.04	0.03	0.01	0.01	1.23	0.37	0.17	0.11	0.09	0.05	0.04
Engineering Piping, $f_{engg.piping}$	1.08	0.58	0.34	0.25	0.18	0.14	0.13	0.09	0.22	0.11	0.05	0.04	0.03	0.03	0.03
Engineering Electric, $f_{engg.elec}$	1.04	0.3	0.15	0.11	0.1	0.09	0.05	0.04	1.22	0.41	0.2	0.25	0.13	0.1	0.09
Engineering Instrument, $f_{engg.inst}$	1.85	0.72	0.36	0.25	0.2	0.14	0.13	0.09	1.21	0.36	0.15	0.11	0.09	0.05	0.04
Engineering Civil, $f_{engg.civil}$	0.39	0.11	0.04	0.03	0.03	0.01	0.01	0.01	0.5	0.17	0.09	0.05	0.04	0.03	0.03
Engineering Steel & Concrete, $f_{engg.S\&C}$	0.58	0.24	0.13	0.1	0.09	0.05	0.05	0.04	0.67	0.28	0.15	0.13	0.11	0.09	0.09
Engineering Insulation $f_{engg.insulation}$	0.27	0.09	0.03	0.01	0.01	0.01	0.01	0.01	0.27	0.09	0.03	0.01	0.01	0.01	0.01
Engineering Cost, f_{engg}	**7.43**	**2.73**	**1.38**	**0.99**	**0.8**	**0.6**	**0.51**	**0.38**	**6.54**	**2.21**	**1.08**	**0.89**	**0.65**	**0.48**	**0.43**
Procurement, $f_{procurement}$	1.55	0.52	0.2	0.13	0.09	0.04	0.03	0.03	1.55	0.52	0.2	0.13	0.09	0.04	0.03
Project Control, $f_{project\ control}$	0.37	0.14	0.05	0.04	0.04	0.03	0.03	0.03	0.33	0.11	0.05	0.04	0.03	0.03	0.03
Site Management, $f_{site\ manage}$	0.66	0.42	0.28	0.24	0.2	0.17	0.15	0.11	0.56	0.36	0.25	0.2	0.18	0.15	0.15
Project Management, $f_{project\ manage}$	0.89	0.46	0.29	0.24	0.2	0.17	0.15	0.11	0.76	0.39	0.25	0.2	0.17	0.15	0.14
Administration Cost, $f_{administration}$	**3.47**	**1.54**	**0.83**	**0.65**	**0.53**	**0.39**	**0.36**	**0.28**	**3.2**	**1.38**	**0.76**	**0.57**	**0.46**	**0.37**	**0.34**
Commissioning, $f_{commissioning}$	0.72	0.33	0.17	0.1	0.1	0.05	0.05	0.04	0.62	0.29	0.15	0.11	0.09	0.05	0.04
Total Known Cost, $F_{known\ cost}$	**24.66**	**12.48**	**7.57**	**5.95**	**5.03**	**4.06**	**3.66**	**2.94**	**21.64**	**10.83**	**6.68**	**5.36**	**4.48**	**3.68**	**3.32**
Contingency, $f_{contingency}$	4.99	2.55	1.57	1.24	1.06	0.87	0.78	0.64	4.38	2.22	1.39	1.13	0.95	0.79	0.72
Total Plant Cost, $F_{Total,\ CS}$	**29.65**	**15.03**	**9.13**	**7.2**	**6.1**	**4.93**	**4.44**	**3.59**	**26.02**	**13.05**	**8.07**	**6.48**	**5.43**	**4.47**	**4.04**

Table C2
EDF method's Installation Factors Sheet for fluid handling equipment installation-prepared by Nils Henrik Eldrup, 2020 (USN and SINTEF Tel-Tek).

EDF method installation factors for fluid handling equipment											
Equipment costs (CS) in 1000 €:	0 - 10	10 - 20	20 - 40	40 - 80	80 - 160	160 - 320	320 - 640	640 - 1280	1280 - 2560	2560 - 5120	5120 - 10240
Equipment cost	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Erection cost	0.49	0.33	0.26	0.20	0.16	0.12	0.09	0.07	0.06	0.04	0.03
Piping incl. Erection	2.24	1.54	1.22	0.96	0.76	0.60	0.48	0.38	0.30	0.23	0.19
Electro (equip. & erection)	0.76	0.59	0.51	0.44	0.38	0.32	0.28	0.24	0.20	0.18	0.15
Instrument (equip. & erection)	1.50	1.03	0.81	0.64	0.51	0.40	0.32	0.25	0.20	0.16	0.12
Ground work	0.27	0.21	0.18	0.15	0.13	0.11	0.09	0.08	0.07	0.06	0.05
Steel & concrete	0.85	0.66	0.55	0.47	0.40	0.34	0.29	0.24	0.20	0.17	0.15
Insulation	0.28	0.18	0.14	0.11	0.08	0.06	0.05	0.04	0.03	0.02	0.02
Direct costs	**7.38**	**5.54**	**4.67**	**3.97**	**3.41**	**2.96**	**2.59**	**2.30**	**2.06**	**1.86**	**1.71**
Engineering process	0.44	0.27	0.22	0.18	0.15	0.12	0.10	0.09	0.07	0.06	0.05
Engineering mechanical	0.32	0.16	0.11	0.08	0.06	0.05	0.03	0.03	0.02	0.02	0.01
Engineering piping	0.67	0.46	0.37	0.29	0.23	0.18	0.14	0.11	0.09	0.07	0.06
Engineering el.	0.33	0.20	0.15	0.12	0.10	0.08	0.07	0.06	0.05	0.04	0.04
Engineering instr.	0.59	0.36	0.27	0.20	0.16	0.12	0.10	0.08	0.06	0.05	0.04
Engineering ground	0.10	0.05	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Engineering steel & concrete	0.19	0.12	0.09	0.08	0.06	0.05	0.04	0.04	0.03	0.03	0.02
Engineering insulation	0.07	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Engineering	**2.70**	**1.66**	**1.27**	**0.99**	**0.79**	**0.64**	**0.51**	**0.42**	**0.34**	**0.28**	**0.23**
Procurement	1.15	0.38	0.48	0.48	0.24	0.12	0.06	0.03	0.01	0.01	0.00
Project control	0.14	0.08	0.06	0.05	0.04	0.03	0.03	0.02	0.02	0.01	0.01
Site management	0.37	0.28	0.23	0.20	0.17	0.15	0.13	0.11	0.10	0.09	0.09
Project management	0.45	0.30	0.26	0.22	0.18	0.15	0.13	0.11	0.10	0.09	0.08
Administration	**2.10**	**1.04**	**1.03**	**0.94**	**0.63**	**0.45**	**0.34**	**0.27**	**0.23**	**0.20**	**0.18**
Commissioning	0.31	0.19	0.14	0.11	0.08	0.06	0.05	0.04	0.03	0.02	0.02
Identified costs	**12.48**	**8.43**	**7.11**	**6.02**	**4.91**	**4.10**	**3.49**	**3.02**	**2.66**	**2.37**	**2.13**
Contingency	2.50	1.69	1.42	1.20	0.98	0.82	0.70	0.60	0.53	0.47	0.43
Installation factor 2020	**14.98**	**10.12**	**8.54**	**7.22**	**5.89**	**4.92**	**4.19**	**3.63**	**3.19**	**2.84**	**2.56**
Adjustment for material	Equipment & piping factors multiplies with										
Carbon steel (CS)	1.00										
Stainless steel SS316 (welded)	1.75										
Stainless steel SS316, rotating equipment (Machined)	1.30										
Glass-reinforced plastic (GRP)	1.40										
Exotic material (welded)	2.50										
Exotic material, rotating equipment (machined)	1.75										

Table C2a
EDF method's Installation Factors Sheet for Solid handling equipment installation-prepared by Nils Henrik Eldrup, 2020 (USN and SINTEF Tel-Tek).

EDF method installation factors for solid handling equipment											
Equipment costs (CS) in 1000 €:	0 - 10	10 - 20	20 - 40	40 - 80	80 - 160	160 - 320	320 - 640	640 - 1280	1280 - 2560	2560 - 5120	5120 - 10240
Equipment cost	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Erection cost	0.94	0.64	0.50	0.39	0.31	0.24	0.19	0.15	0.12	0.09	0.07
Piping incl. Erection	0.45	0.31	0.24	0.19	0.15	0.12	0.10	0.08	0.06	0.05	0.04
Electro (equip & erection)	1.20	0.90	0.75	0.63	0.53	0.44	0.37	0.31	0.26	0.22	0.19
Instrument (equip. & erection)	0.60	0.41	0.33	0.26	0.20	0.16	0.13	0.10	0.08	0.06	0.05
Ground work	0.71	0.51	0.42	0.34	0.28	0.23	0.19	0.15	0.13	0.10	0.09
Steel & concrete	1.30	0.96	0.80	0.66	0.55	0.46	0.38	0.32	0.26	0.22	0.18
Insulation	0.28	0.18	0.14	0.11	0.08	0.06	0.05	0.04	0.03	0.02	0.02
Direct costs	**6.48**	**4.92**	**4.18**	**3.58**	**3.10**	**2.71**	**2.40**	**2.15**	**1.94**	**1.77**	**1.63**
Engineering process	0.44	0.27	0.22	0.18	0.15	0.12	0.10	0.09	0.07	0.06	0.05
Engineering mechanical	0.47	0.27	0.20	0.15	0.11	0.09	0.07	0.05	0.04	0.03	0.03
Engineering piping	0.13	0.09	0.07	0.06	0.05	0.04	0.03	0.02	0.02	0.01	0.01
Engineering el.	0.44	0.27	0.21	0.17	0.14	0.11	0.09	0.08	0.07	0.06	0.05
Engineering instr.	0.32	0.17	0.12	0.09	0.07	0.05	0.04	0.03	0.02	0.02	0.01
Engineering ground	0.16	0.10	0.07	0.06	0.04	0.04	0.03	0.02	0.02	0.02	0.01
Engineering steel & concrete	0.25	0.16	0.13	0.10	0.08	0.07	0.06	0.05	0.04	0.03	0.03
Engineering insulation	0.07	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Engineering	**2.30**	**1.38**	**1.05**	**0.82**	**0.65**	**0.53**	**0.43**	**0.35**	**0.29**	**0.24**	**0.20**
Procurement	1.15	0.38	0.48	0.48	0.24	0.12	0.06	0.03	0.01	0.01	0.00
Project control	0.11	0.07	0.05	0.04	0.03	0.03	0.02	0.02	0.01	0.01	0.01
Site management	0.32	0.25	0.21	0.18	0.16	0.14	0.12	0.11	0.10	0.09	0.08
Project management	0.39	0.27	0.23	0.19	0.16	0.13	0.12	0.10	0.09	0.08	0.07
Administration	**1.98**	**0.96**	**0.97**	**0.89**	**0.59**	**0.42**	**0.32**	**0.26**	**0.22**	**0.19**	**0.17**
Commissioning	0.28	0.17	0.13	0.10	0.08	0.06	0.05	0.04	0.03	0.02	0.02
Identified costs	**11.04**	**7.44**	**6.33**	**5.40**	**4.42**	**3.72**	**3.19**	**2.79**	**2.47**	**2.22**	**2.01**
Contingency	2.21	1.49	1.27	1.08	0.88	0.74	0.64	0.56	0.49	0.44	0.40

(*continued on next page*)

Table C2a (*continued*)

Installation factor 2020	**13.24**	**8.93**	**7.60**	**6.48**	**5.30**	**4.46**	**3.83**	**3.34**	**2.96**	**2.66**	**2.42**
Adjustment for material	Equipment & piping factors multiplies with										
Carbon steel (CS)	1.00										
Stainless steel SS316 (welded)	1.75										
Stainless steel SS316, rotating equipment (Machined)	1.30										
Glass-reinforced plastic (GRP)	1.40										
Exotic material (welded)	2.50										
Exotic material, rotating equipment (machined)	1.75										

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