Heat exchanger network design

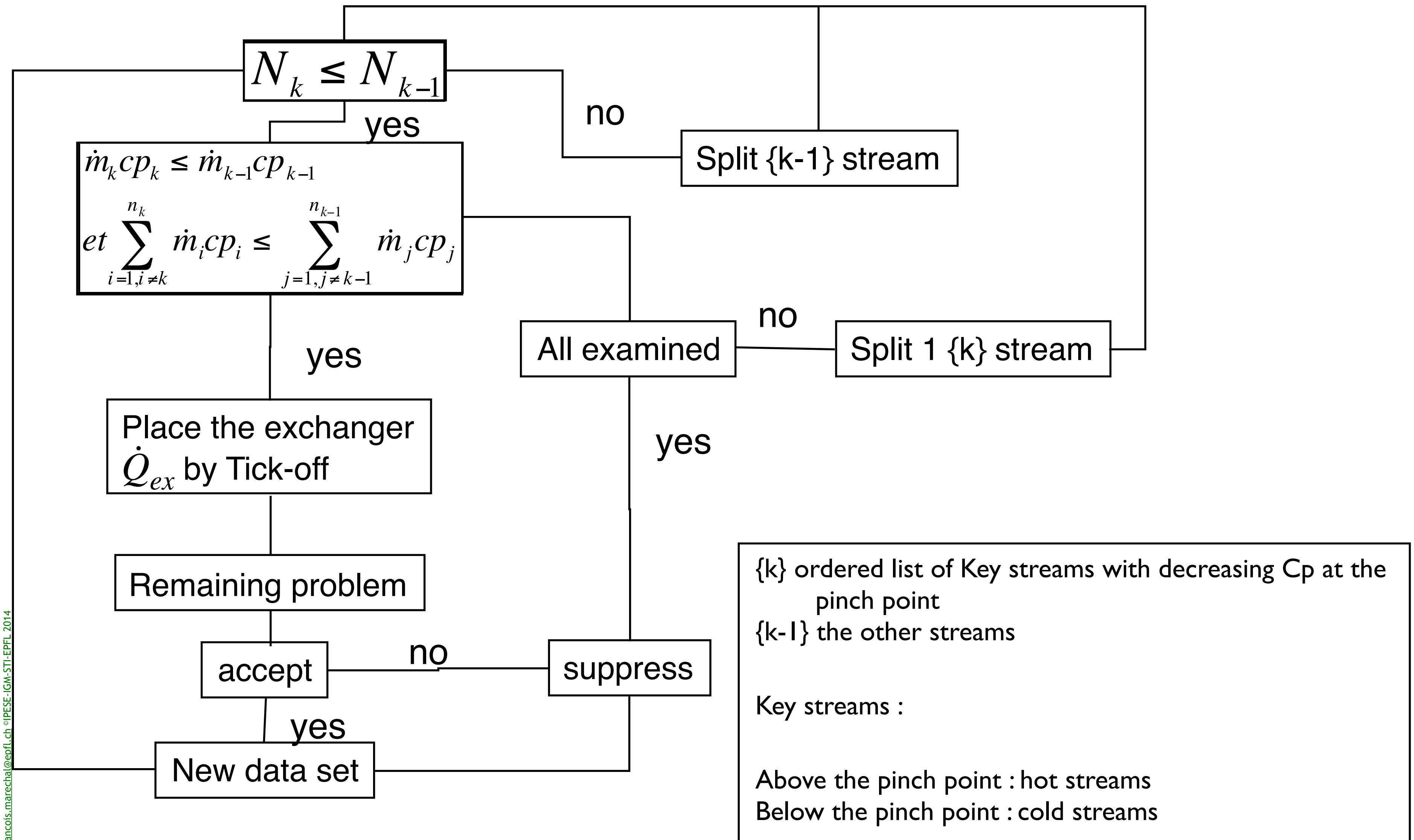
Pinch design method

Loop and paths for reducting the number of heat exchangers

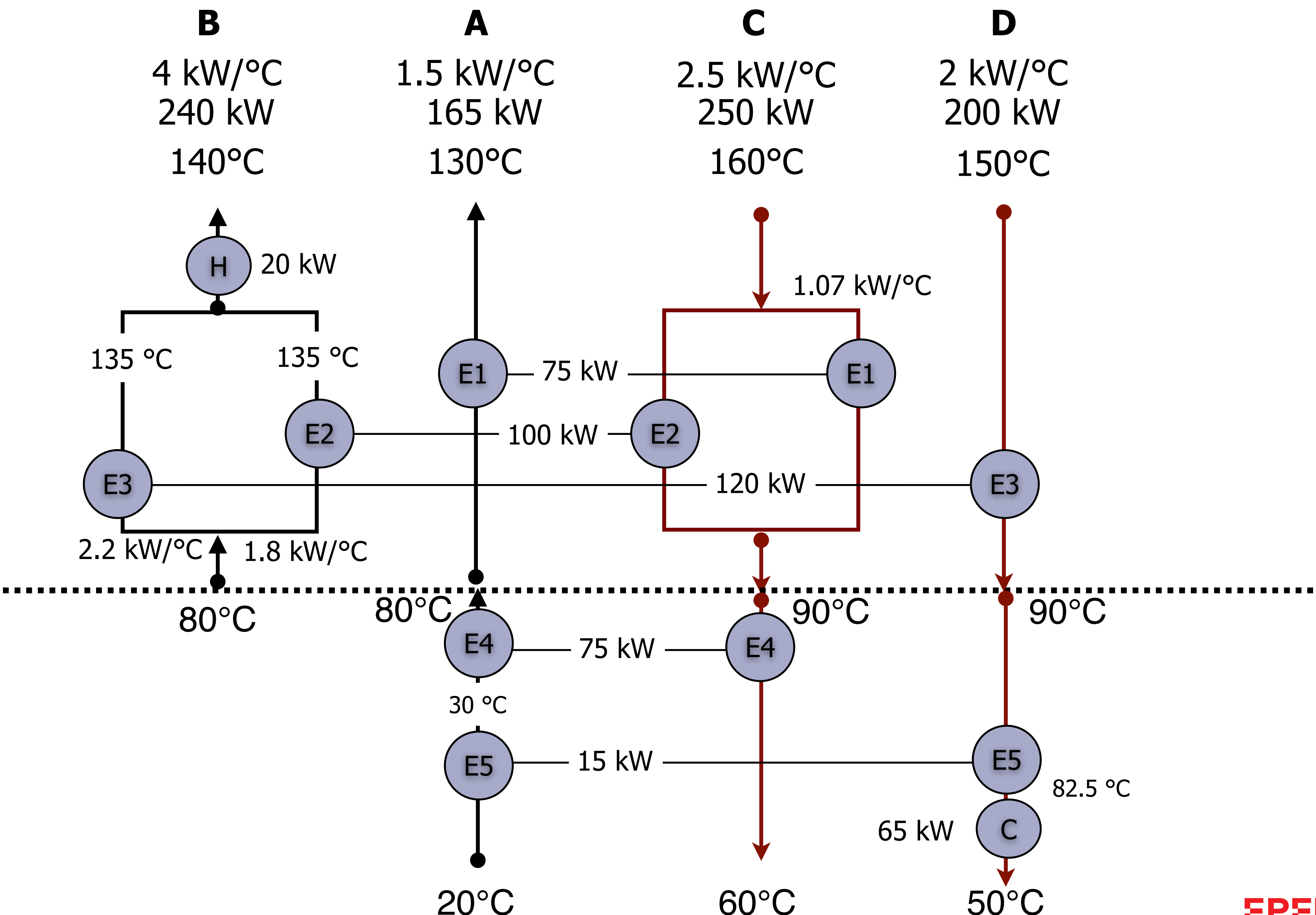
Prof. François Marechal

EPFL

The synthesis of the HEN synthesis algorithm



Pinch design method design



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Heat exchangers after Pinch design method

Operating cost = 2325 CHF/year

	T_{hot} [C]	ΔT_{hot} [C]	T_{cold} [C]	ΔT_{cold} [C]	ΔT_{lm} [C]	$\dot{Q}$ [kW]	A $[m^2]$	Cost [CHF]
	160		90					
E1		30		10	18.20	75.0	16.5	32945
	130		80					
	160		90					
E2		25		10	16.37	100.0	24.4	43327
	135		80					
	150		90					
E3		15		10	12.33	120.0	38.9	60055
	135		80					
	90		60					
E4		10		30	18.20	75.0	16.5	32947
	80		30					
	90		82.5					
E5		43.3		62.5	61.24	15.0	1.0	4630
	30		20					
Total						385.0	97.3	173905

Table 7: Heat Exchangers obtained with Pinch Design Method

Number of exchangers : 5+2 = 7 = 4+2-1+3-1

Fluid heat transfer coefficient U = 0.5 kW/C°/m2

Is it the best solution ?

- **Reduce the number of heat exchangers**
  - Path following
  - Loop following
- **Find the best compromise between**
  - Investment
    - Less heat exchangers
    - Other DTmin value (Exchanger minimum approach temperature : EMAT for each exchanger)
  - Operating cost (more/less heat consumption)
  - Other good arguments
    - operability
    - safety
    - retrofit

Final results : comparing solutions

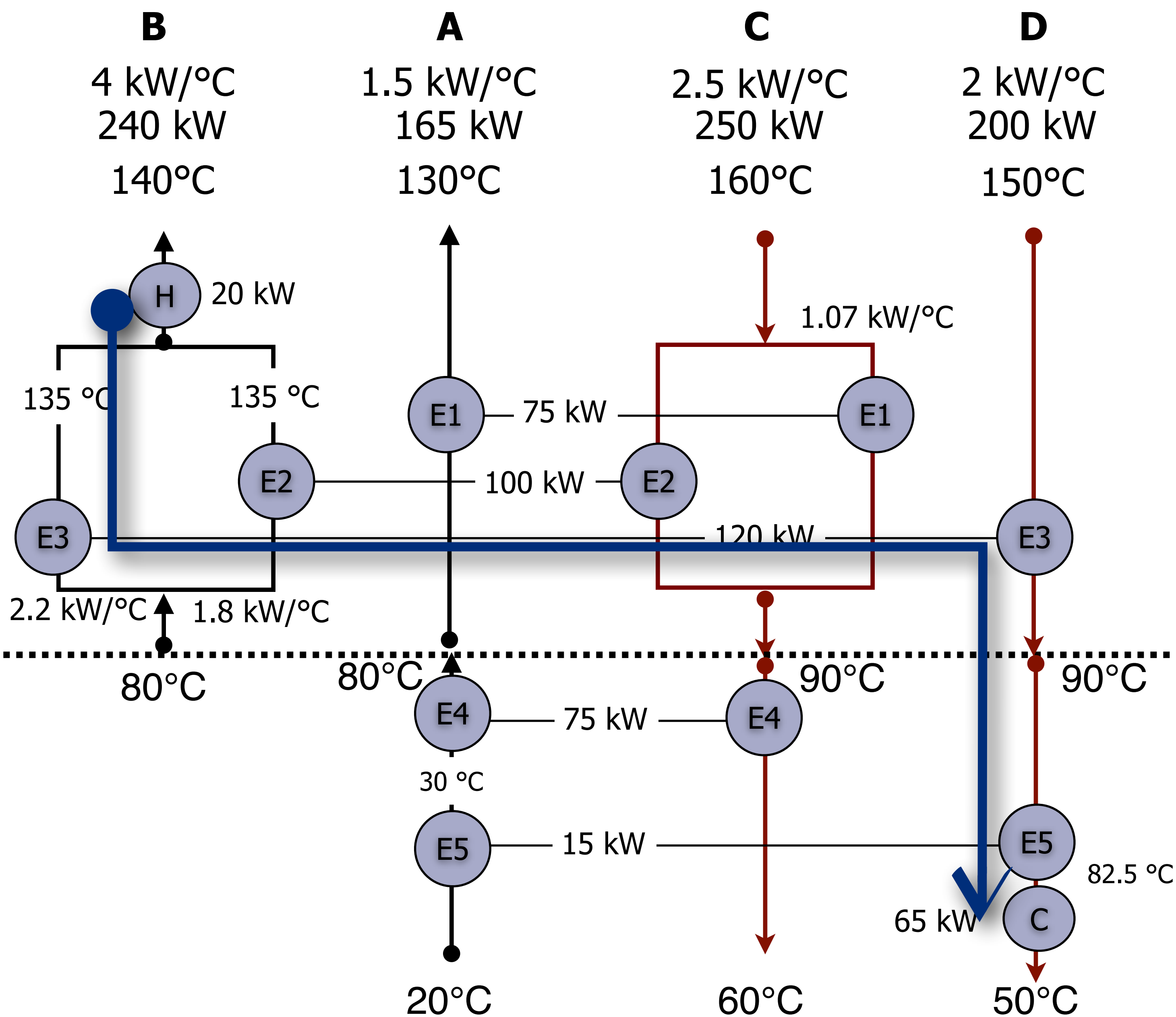
	Invest $[CHF]$	CAPEX $[CHF/year]$	OPEX $[CHF/year]$	Total $[CHF/year]$	Nb Ex.
0	173905	20340	2352	22692	7

Table 14: Summary of the heat exchanger network design

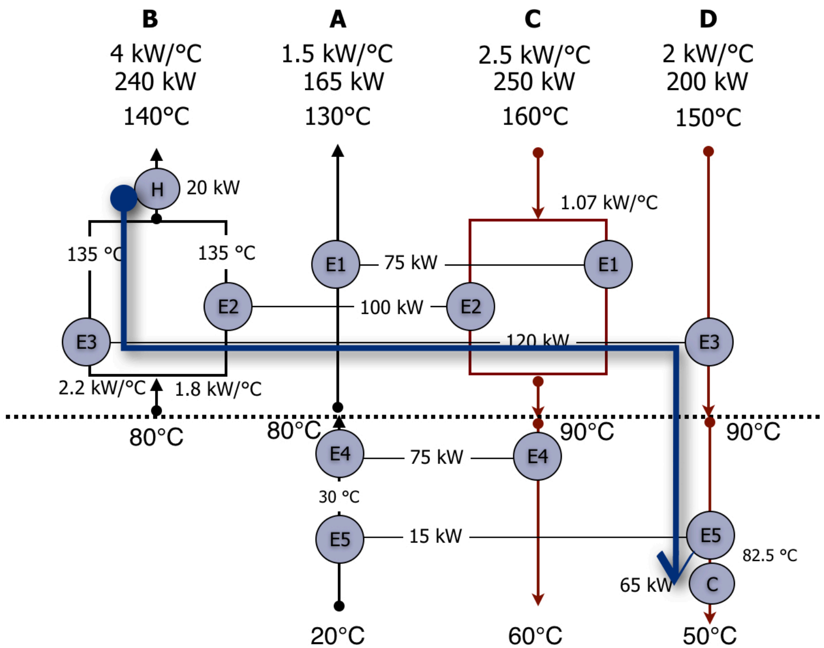
Path following technique

- **A path indicates the path of the heat from one hot utility to one cold utility through heat exchangers**
- **If I'm adding 1 kW of hot utility**
  - what are the heat exchangers that are affected ?
    - the next one of the path on the cold stream reduces by 1 kW, therefore on the hot side there will be the need to increase the heat load of one on the hot stream, etc… until we reach a cold utility which will increase by 1 kW.
  - in a path adding heat in the hot utility means reducing the heat exchanged in the next heat exchanger ... up to the cold utility is reached.
- **One could choose the heat load to suppress one of the heat exchangers in the path.**

Path following through E3

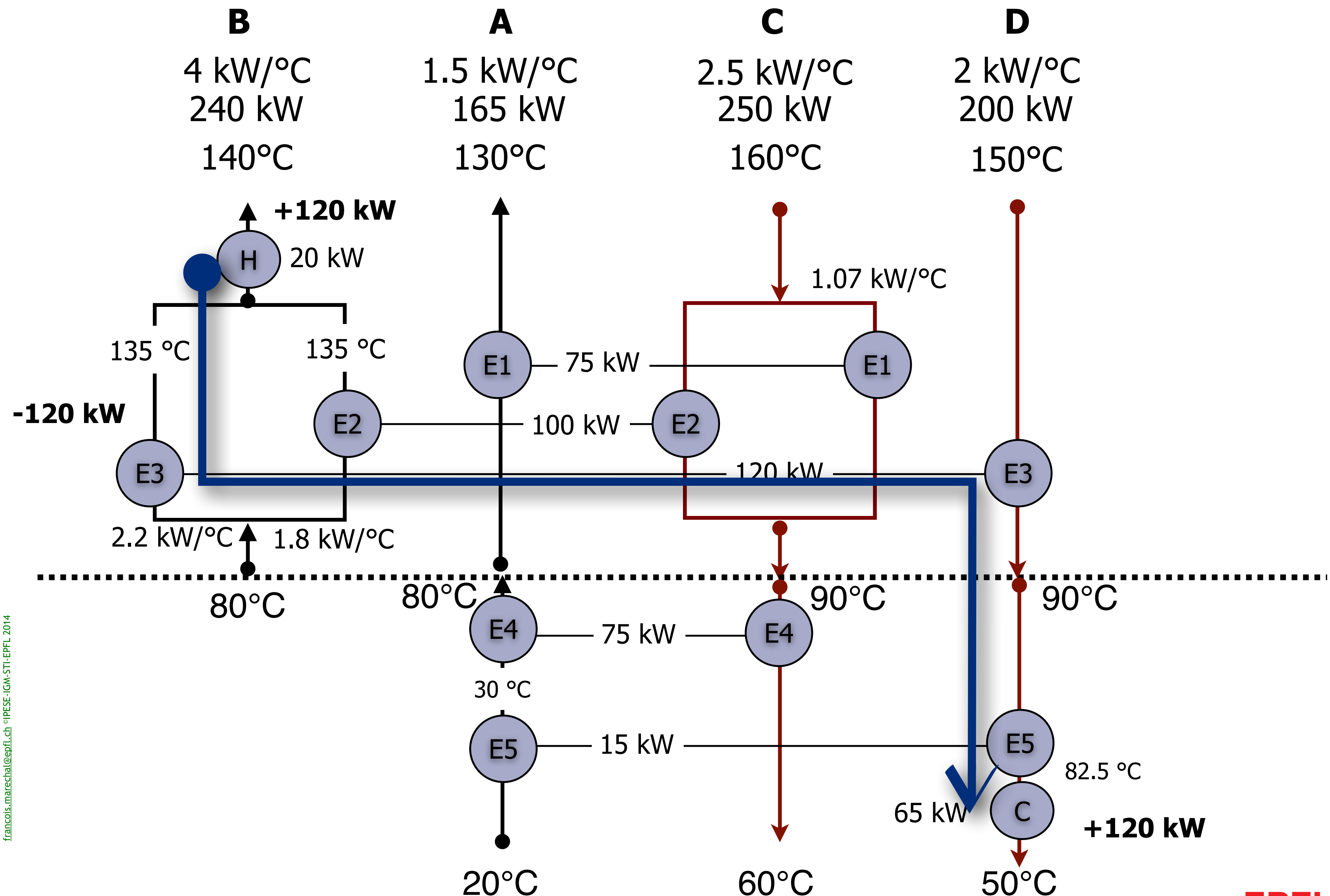


Path explanation



- There exist a path that goes from hot utility (H) on cold stream (B) to the cold utility (C) on hot stream (D) via the heat exchanger E3 that links the cold stream B and the hot stream D
- if the load of E3 is reduced by X kW,
- there will be less heat recovery for stream B therefore the hot utility will have to be increased by X kW to compensate the heat recovery reduction for the cold stream B,
- similarly the cold utility will have to increase by X kW to compensate from the fact that the hot stream D in exchanger E3 has not given the heat to the cold stream B and therefore has more heat that has to be evacuated by the cold utility.
- When X is equal to the heat load of the heat exchanger E3, the heat exchanger will vanish. As a consequence the investment disappears at the price of an increase of both the hot and the cold utility.
- The energy cost will have to be compared with the CAPEX reduction

Path following E3



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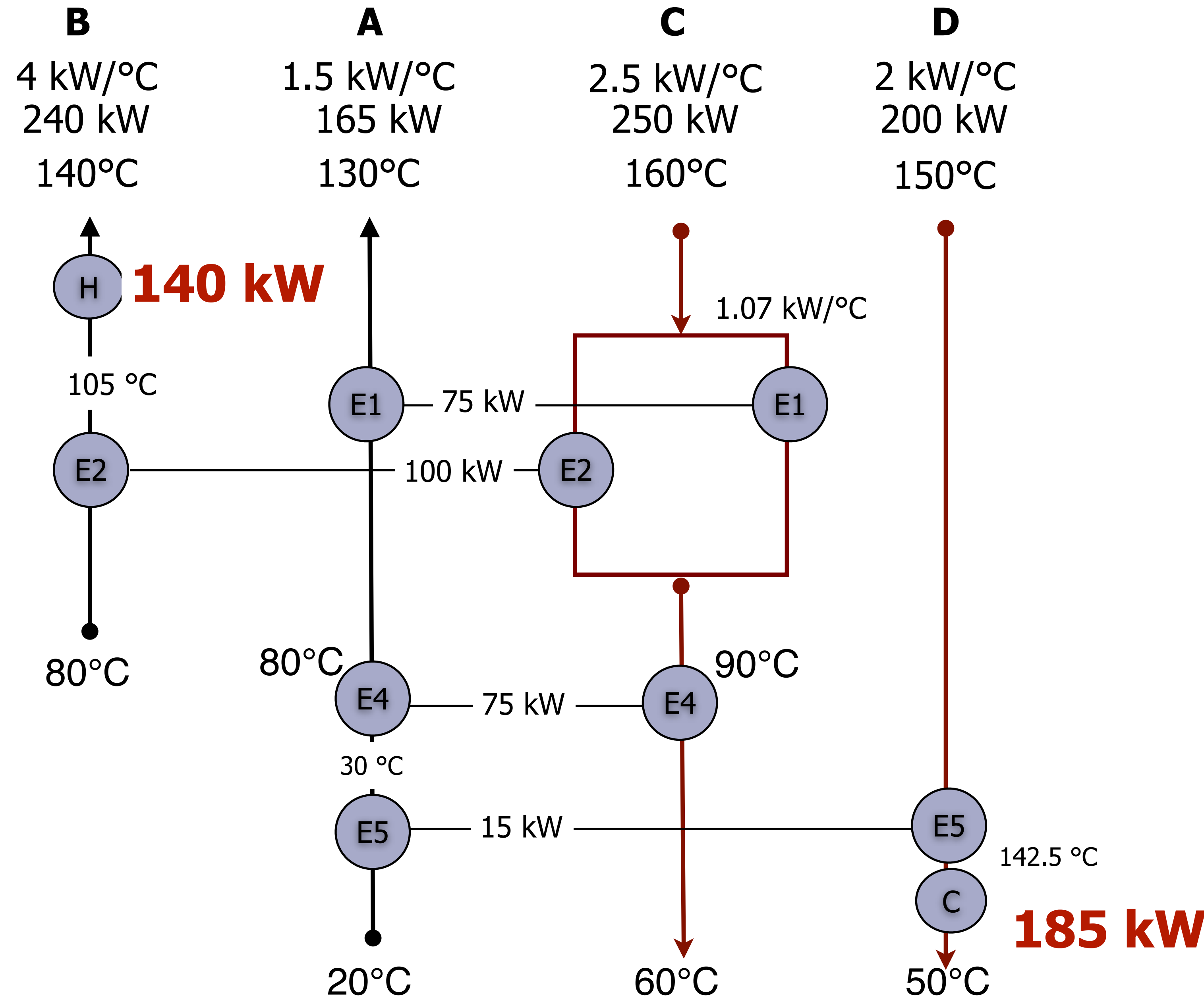
Path following supressing E3 : Network design



Suppression of E3 : solution

Operating cost : 16471 CHF/year

	T_{hot} [C]	ΔT_{hot} [C]	T_{cold} [C]	ΔT_{cold} [C]	ΔT_{lm} [C]	$\dot{Q}$ [kW]	A [m^2]	Cost [CHF]
	160		90					
E1		30		10	18.20	75.0	16.5	32945
	130		80					
	160		90					
E2		25		10	26.40	100.0	15.2	31041
	105		80					
	90		60					
E4		10		30	18.20	75.0	16.5	32947
	80		30					
	150		142.5					
E5		120		122.5	121.25	15.0	0.5	2830
	30		20					
Total						265.0	48.7	99723

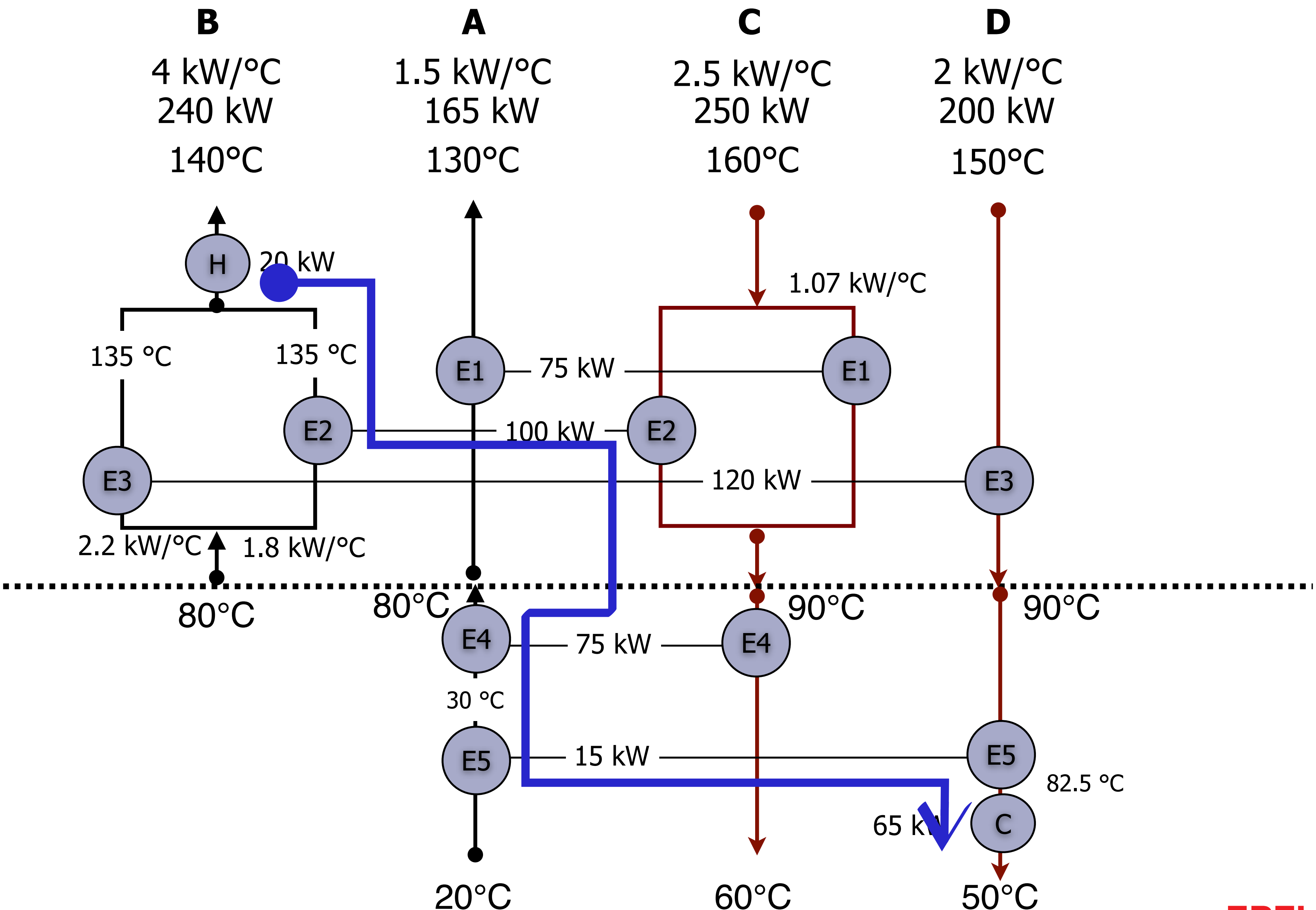
Table 13: Heat Exchanger network after removing E3 with path following technique

Final results : comparing solutions

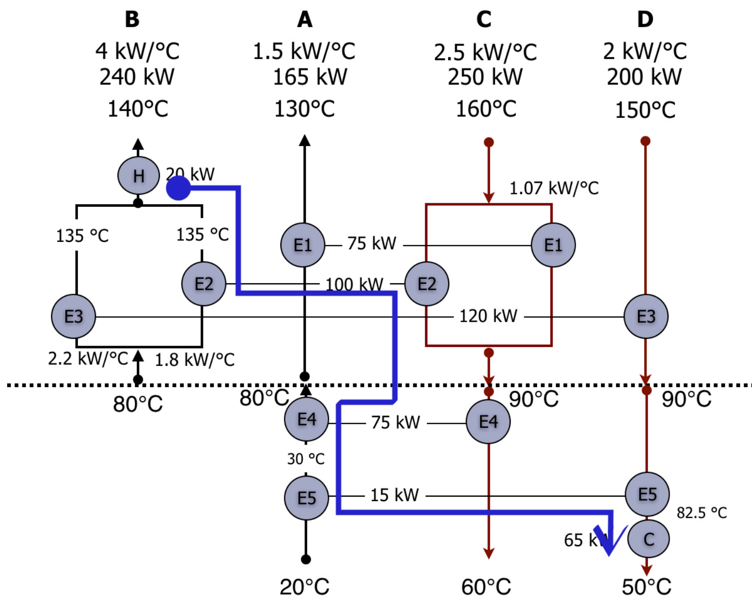
	Invest [CHF]	CAPEX [$CHF/year$]	OPEX [$CHF/year$]	Total [$CHF/year$]	Nb Ex.
0	173905	20340	2352	22692	7
6	99723	11664	16471	28135	6

Table 14: Summary of the heat exchanger network design

Path following 2

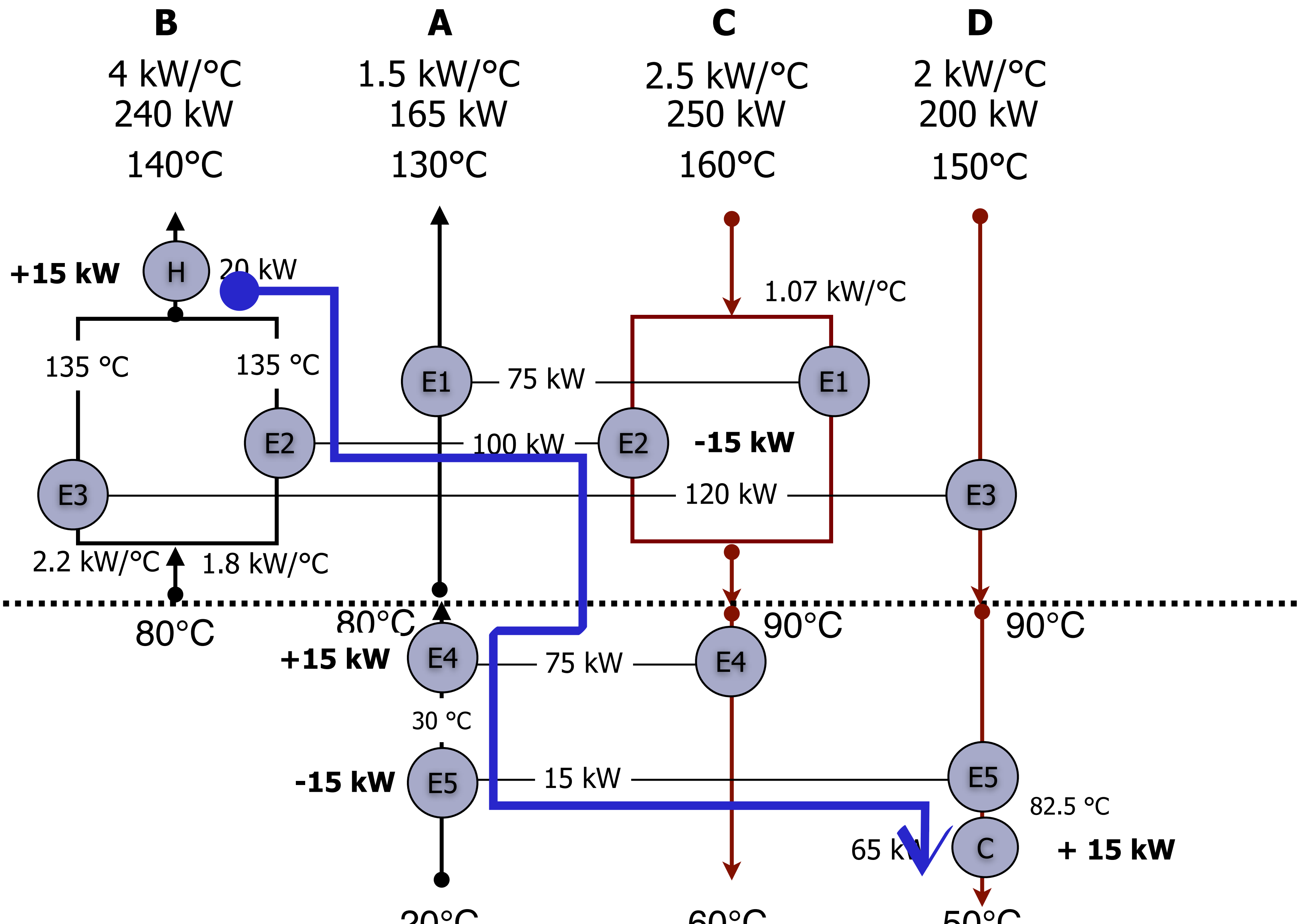


Path following 2

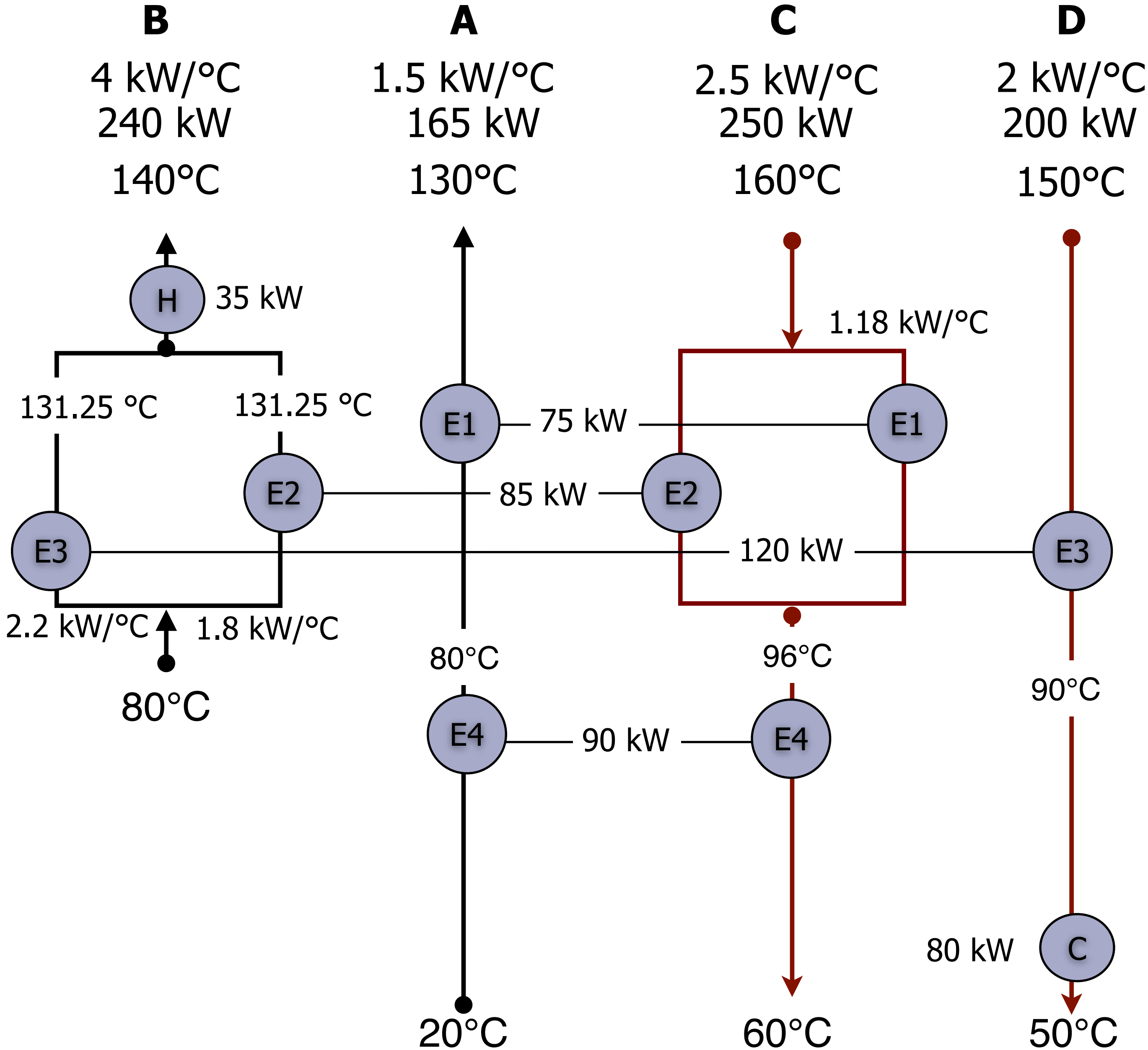


- Path can follow more then one heat exchanger to link the hot utility (H) and the cold utility (C).
- For example a reduction by X kW in (E2) will result will imply on the one hand an increase of the hot utility (H) to close the energy balance of stream B and on the other hand an increase by X kW in (E4) in order to maintain the energy balance of the stream C. The increase in (E4) will therefore lead to a decrease by X kW of (E5) to close the balance of stream A which in turns leads to an increase of X kW in the cold utility (C).
- When X reaches the smallest value of the heat loads of heat exchangers in the path, the heat exchanger will disappear and the increase of the cost of energy will have to be compared with the benefit of not adding a heat exchanger.
- Note that all the temperatures of the heat exchangers have to be recalculated to reflect the changes in heat load of the heat exchangers. In addition feasibility of the heat-exchange (the temperature differences and both hot and cold ends have to be positive) has to be verified. It is however possible that some temperature differences will be lower than the ΔTmin.

Path following 2



Path following 2



Operating cost : 4118 CHF/year

	T_{hot} [C]	ΔT_{hot} [C]	T_{cold} [C]	ΔT_{cold} [C]	ΔT_{lm} [C]	$\dot{Q}$ [kW]	A [m^2]	Cost [CHF]
	160		96					
E1		30		16	22.27	75.0	13.5	28585
	130		80					
	160		96					
E2		28.75		16	21.76	85.0	15.6	31719
	131.25		80					
	150		90					
E3		18.75		10	13.92	120.0	34.5	55196
	131.25		80					
	96		60					
E4		16		40	26.19	90.0	13.7	28991
	80		20					
Total						360.0	77.3	133491

Table 11: Heat Exchangers obtained with Pinch Design Method

Final results : comparing solutions

	Invest $[CHF]$	CAPEX $[CHF/year]$	OPEX $[CHF/year]$	Total $[CHF/year]$	Nb Ex.
0	173905	20340	2352	22692	7
4	**133491**	**15613**	**4118**	**19731**	**6**
6	99723	11664	16471	28135	6

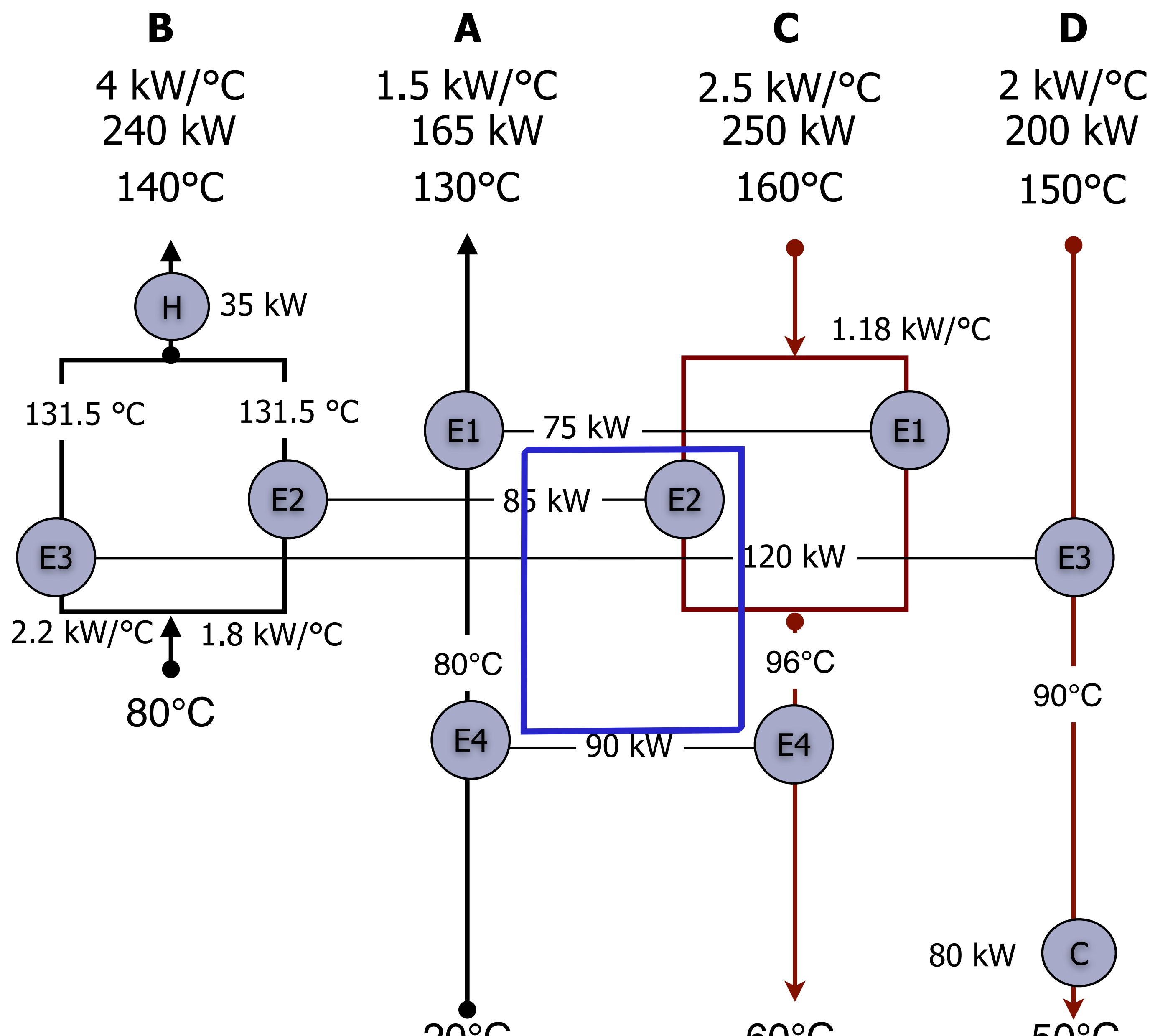
Table 14: Summary of the heat exchanger network design

Loop following technique

- **A loop identifies a list of heat exchangers that exchange twice with the same hot and cold streams.**
- **If I'm adding 1 kW to one heat exchanger in the loop**
  - the neighbouring exchanger will reduce by 1 KW then the next one will increase until we are back to the first one ?
  - The energy balance is not changed (i.e. no increase in hot and cold utility).
  - The heat distribution between the heat exchangers in the loop is changed

- **One could choose the heat load distribution change to suppress one of the heat exchangers in the loop.**

Loops in heat exchanger networks



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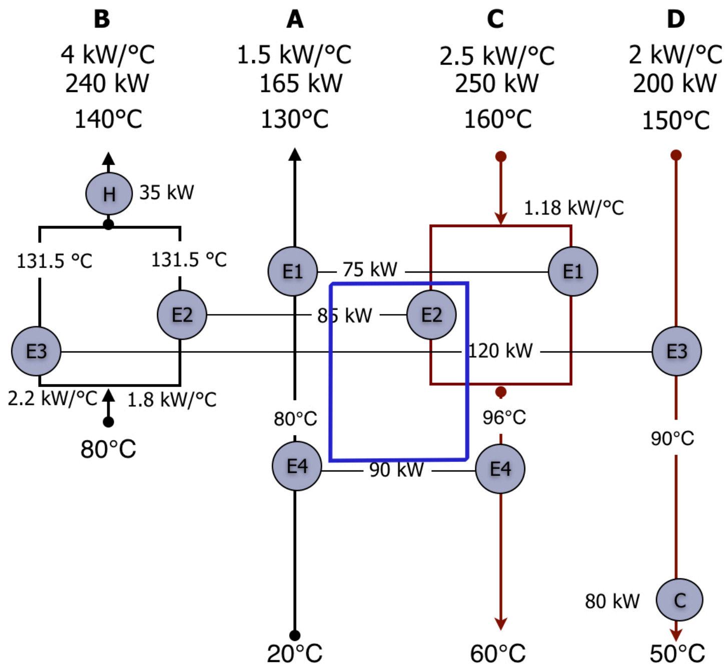
Loops in heat exchanger networks



- Streams A and Stream C are involved in two heat exchangers (E1) and (E4). When increasing (decreasing) the heat load of (E1) by X kW, the heat load of (E4) will be reduced (resp increased) by X kW to maintain the heat balance of both streams A and C.
- When the decrease is equal to the heat load of one heat exchanger in the loop, the heat exchanger disappears and so its investment.
- The temperatures have to be recalculated and the feasibility of the heat exchange has to be assessed with the new temperatures.
- when the exchanges are feasible there will be no energy cost penalty but there will be on the one hand a CAPEX reduction by the fact that the heat exchanger is suppressed but at the same time a penalty due to the increase of the area in the remaining heat exchangers,
- When the temperatures are such that the heat exchange is impossible, it is possible to reduce the heat load of the remaining heat exchangers and therefore increase the temperature difference by identifying a path from (H) to (C). In such a case there will be an energy penalty in addition to the CAPEX modification.

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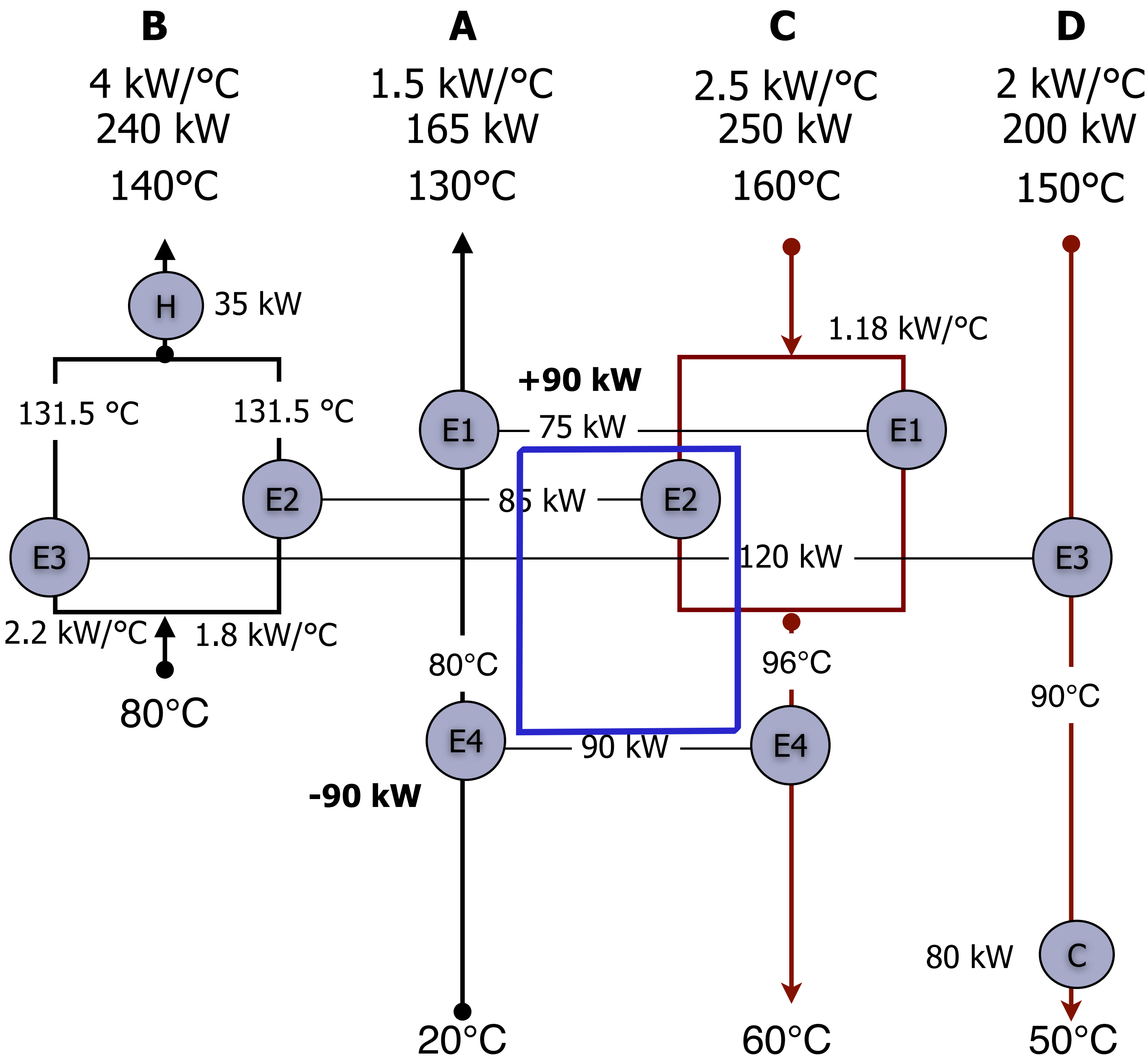
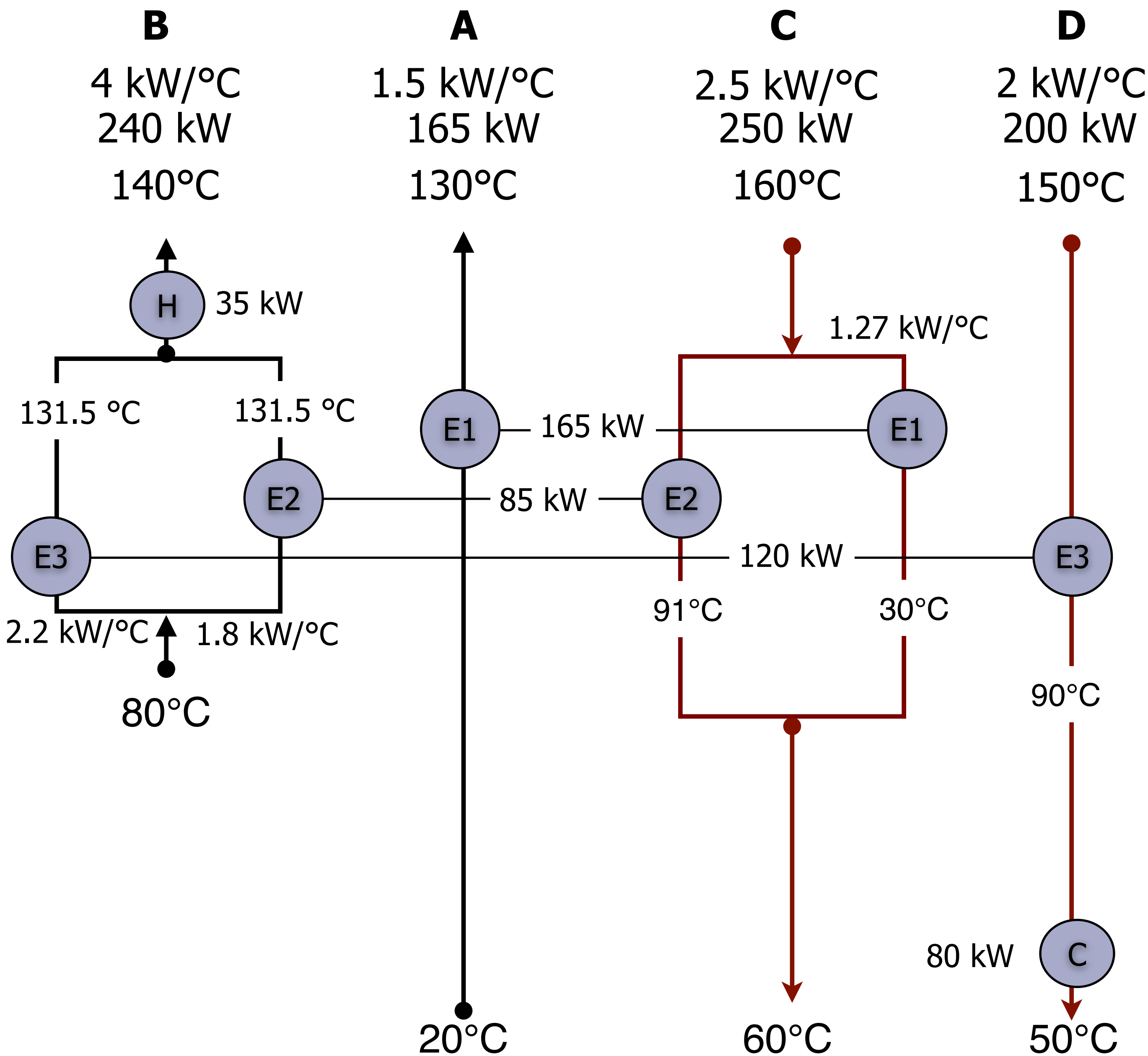
Loop in heat exchanger networks



Loop breaking : new temperatures



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Operating cost : 4118 CHF/year

	T_{hot} [C]	ΔT_{hot} [C]	T_{cold} [C]	ΔT_{cold} [C]	ΔT_{lm} [C]	$\dot{Q}$ [kW]	A [m^2]	Cost [CHF]
	160		30					
E1		30		10	18.20	165.0	36.3	57165
	130		20					
	160		91					
E2		28.75		16	18.48	85.0	18.4	35563
	131.25		80					
	150		90					
E3		18.75		10	13.92	120.0	34.5	55196
	131.25		80					
Total						360.0	89.2	147924

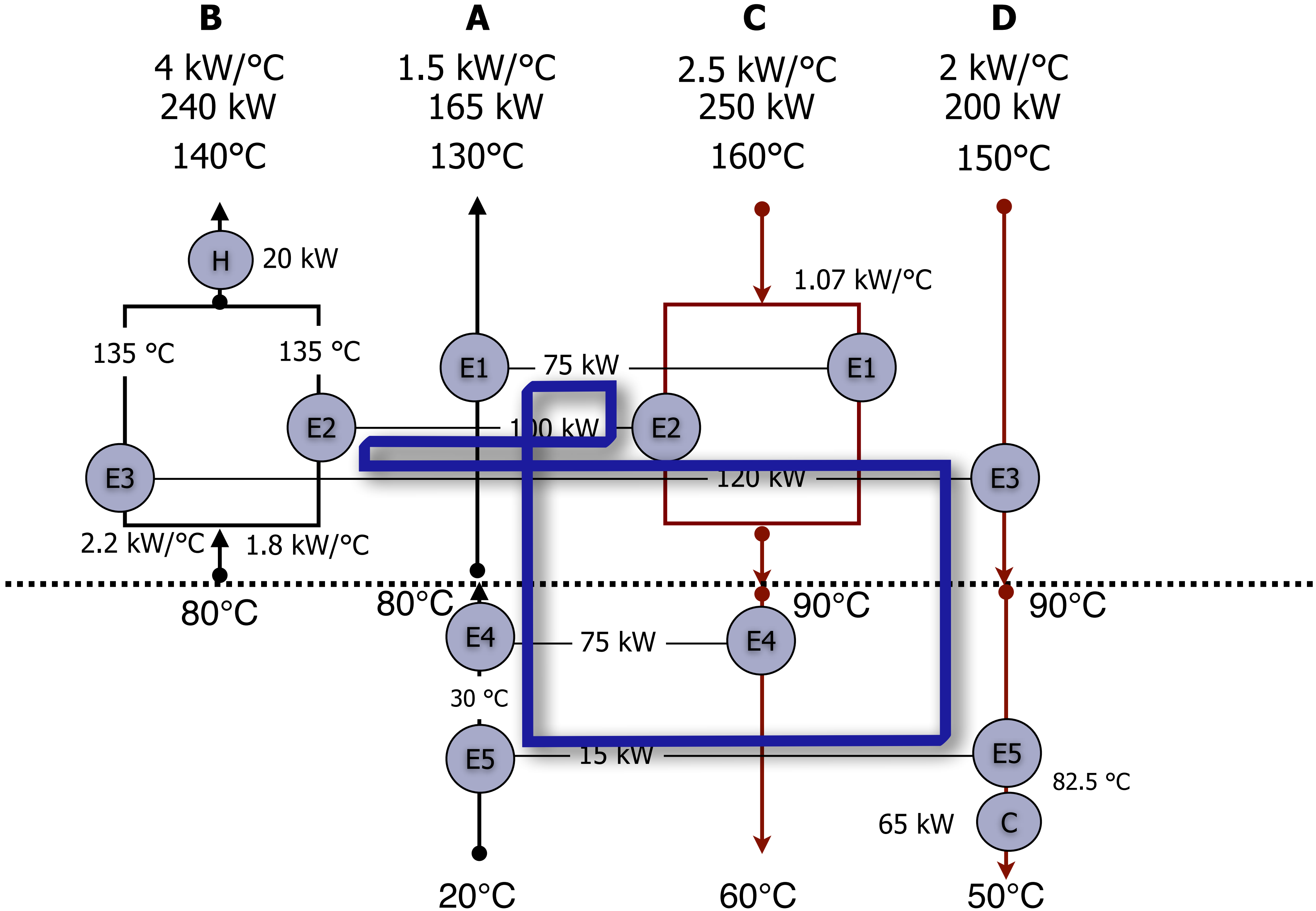
Table 12: Heat Exchangers without E4

Final results : comparing solutions

	Invest $[CHF]$	CAPEX $[CHF/year]$	OPEX $[CHF/year]$	Total $[CHF/year]$	Nb Ex.
0	173905	20340	2352	22692	7
4	**133491**	**15613**	**4118**	**19731**	**6**
5	147924	17301	4118	21419	5
6	99723	11664	16471	28135	6

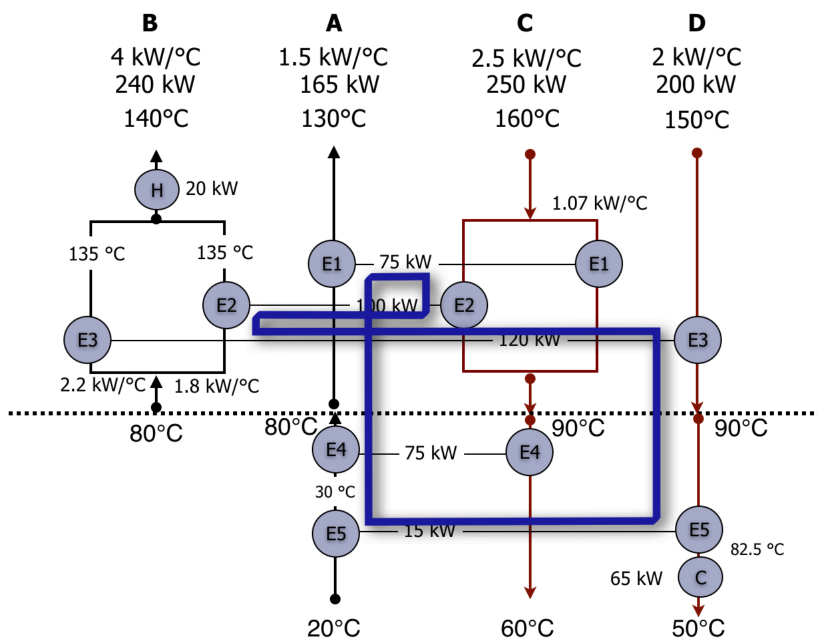
Table 14: Summary of the heat exchanger network design

Loops



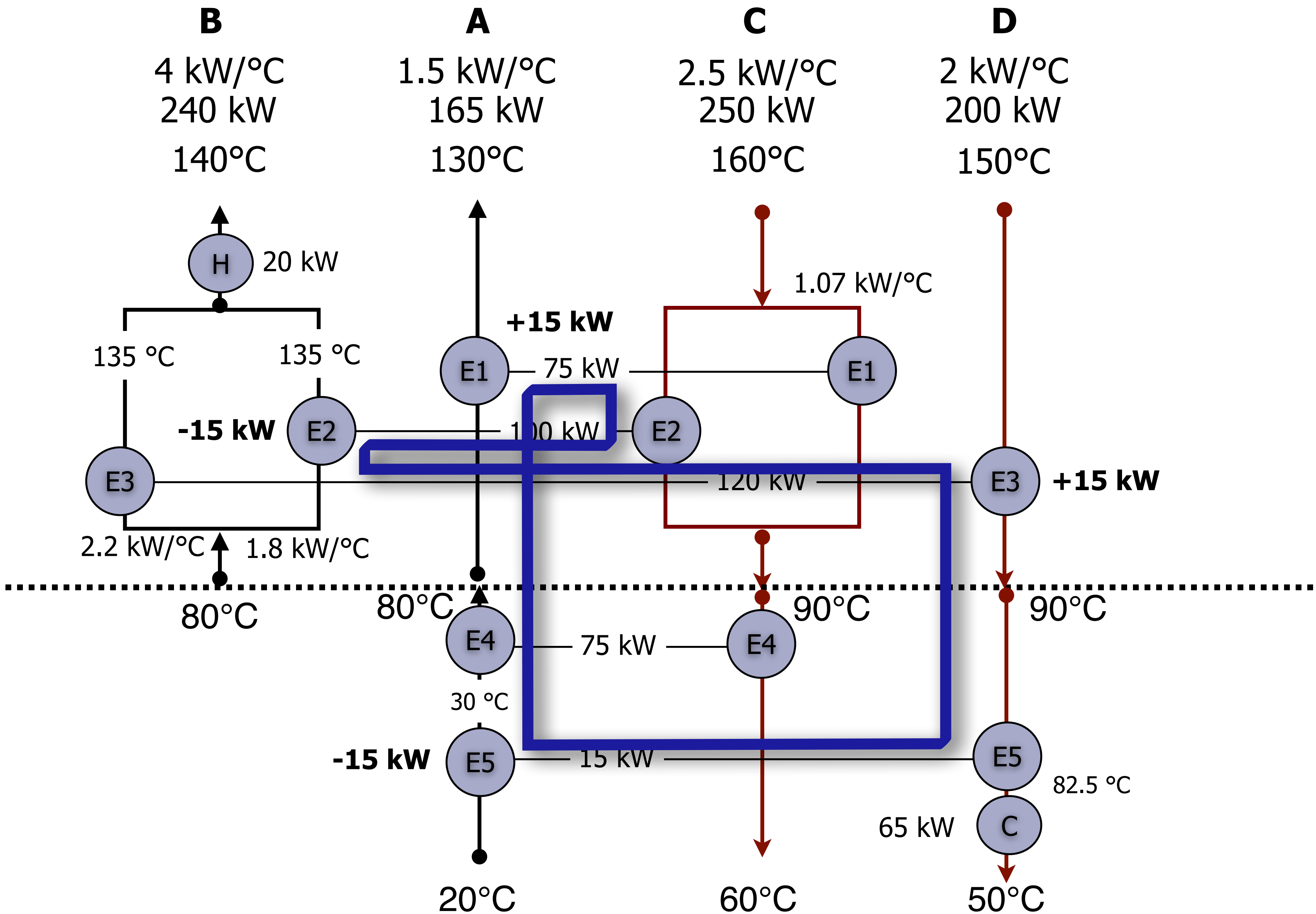
B
4 kW/°C
240 kW
140°C
A
1.5 kW/°C
165 kW
130°C
C
2.5 kW/°C
250 kW
160°C
D
2 kW/°C
200 kW
150°C
H
20 kW
135 °C
135 °C
1.07 kW/°C
E1
75 kW
E1
E2
100 kW
E2
E3
120 kW
E3
2.2 kW/°C
1.8 kW/°C
80°C
80°C
90°C
90°C
E4
75 kW
E4
30 °C
E5
15 kW
E5
82.5 °C
65 kW
C
20°C
60°C
50°C

loops 2



- loops can have more than 2 heat exchangers, in such a case, there will be sucession of + X, -X along the loop.
- For example in the example above, stream A, B, C, D exchange heat more than once. if the heat load of (E1) is reduced by X kW, the heat load of (E2) will increase by X kW to preserve the balance of stream C. In order to preserve the heat balance of stream B, the heat load of (E3) will have to increase by X kW. As a consequence in order to preserve the balance of stream D, the heat load of (E5) will have to be reduced by X kW. As this is a loop this reduction was also needed to close the energy balance of the stream A.
- Choosing the value of X as being the smallest of the heat exchangers in the loop will allow to eliminate a heat exchanger.
- All the temperatures will have to be recalculated as all the heat loads in the heat exchangers change and that the hot and cold utility are not changes.
- If the temperatures differences are positive the heat exchanger network is feasible and the new CAPEX can be calculated.
- if the temperature differences are negative, a path between the hot and the cold utility will have to be identified and an energy penalty will have to be accepted to have feasible heat exchanges

Loops



B
4 kW/°C
240 kW
140°C
A
1.5 kW/°C
165 kW
130°C
C
2.5 kW/°C
250 kW
160°C
D
2 kW/°C
200 kW
150°C
H
20 kW
135 °C
135 °C
-15 kW
E1
E2
E3
+15 kW
75 kW
100 kW
120 kW
1.07 kW/°C
+15 kW
2.2 kW/°C
1.8 kW/°C
80°C
80°C
90°C
90°C
E4
75 kW
30 °C
-15 kW
E5
15 kW
82.5 °C
65 kW
C
20°C
60°C
50°C

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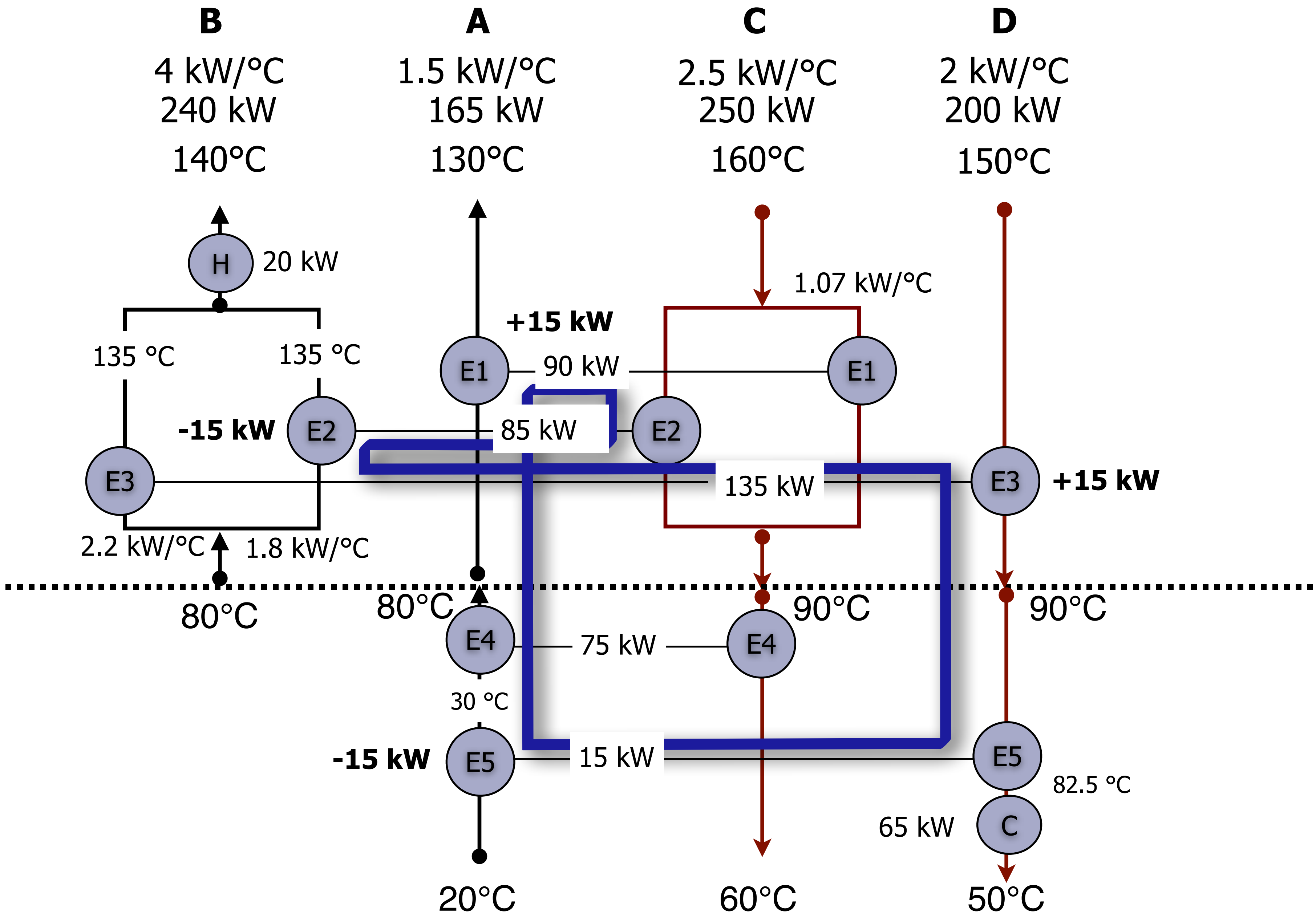
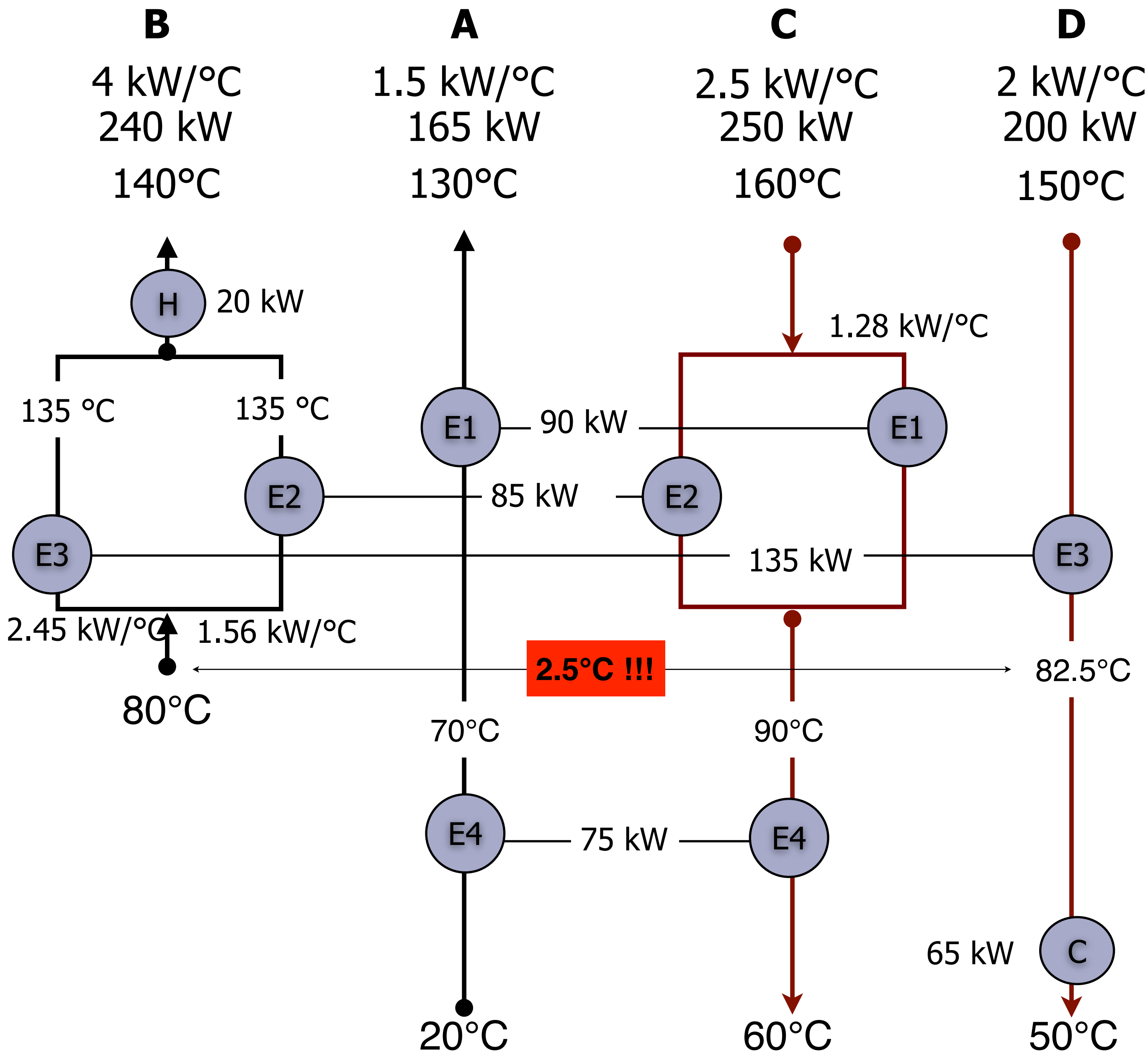
Loops



B
4 kW/°C
240 kW
140°C
A
1.5 kW/°C
165 kW
130°C
C
2.5 kW/°C
250 kW
160°C
D
2 kW/°C
200 kW
150°C
H
20 kW
135 °C
135 °C
-15 kW
E2
E3
2.2 kW/°C
1.8 kW/°C
80°C
+15 kW
E1
90 kW
E1
1.07 kW/°C
85 kW
E2
135 kW
E3
+15 kW
80°C
E4
75 kW
E4
90°C
90°C
30 °C
-15 kW
E5
15 kW
E5
82.5 °C
65 kW
C
20°C
60°C
50°C

Loops : recalculate temperatures



- operating cost : 2352 CHF/year

	T_{hot} [C]	ΔT_{hot} [C]	T_{cold} [C]	ΔT_{cold} [C]	ΔT_{lm} [C]	$\dot{Q}$ [kW]	A [m^2]	Cost [CHF]
	160		90					
E1		30		20	24.66	90.0	14.6	30238
	130		70					
	160		90					
E2		25		10	16.37	85.0	20.8	38706
	135		80					
	150		82.5					
E3		15		2.5	6.98	135.0	77.4	97211
	135		80					
	90		60					
E4		20		40	28.85	75.0	10.4	23846
	70		20					
Total						385.0	123.2	190001

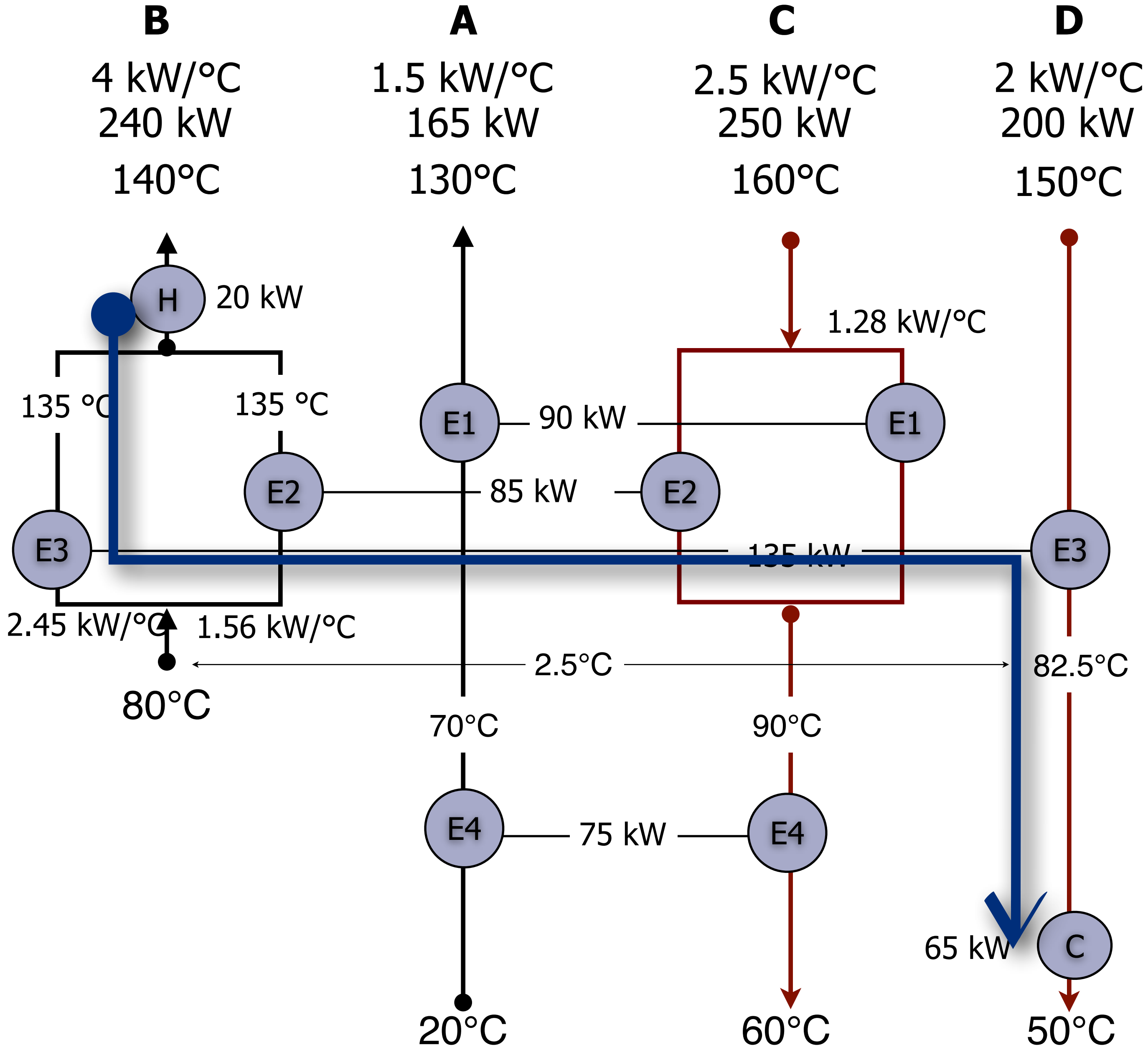
Table 9: Heat Exchangers after suppression of E5 using loop2

Final results : comparing solutions

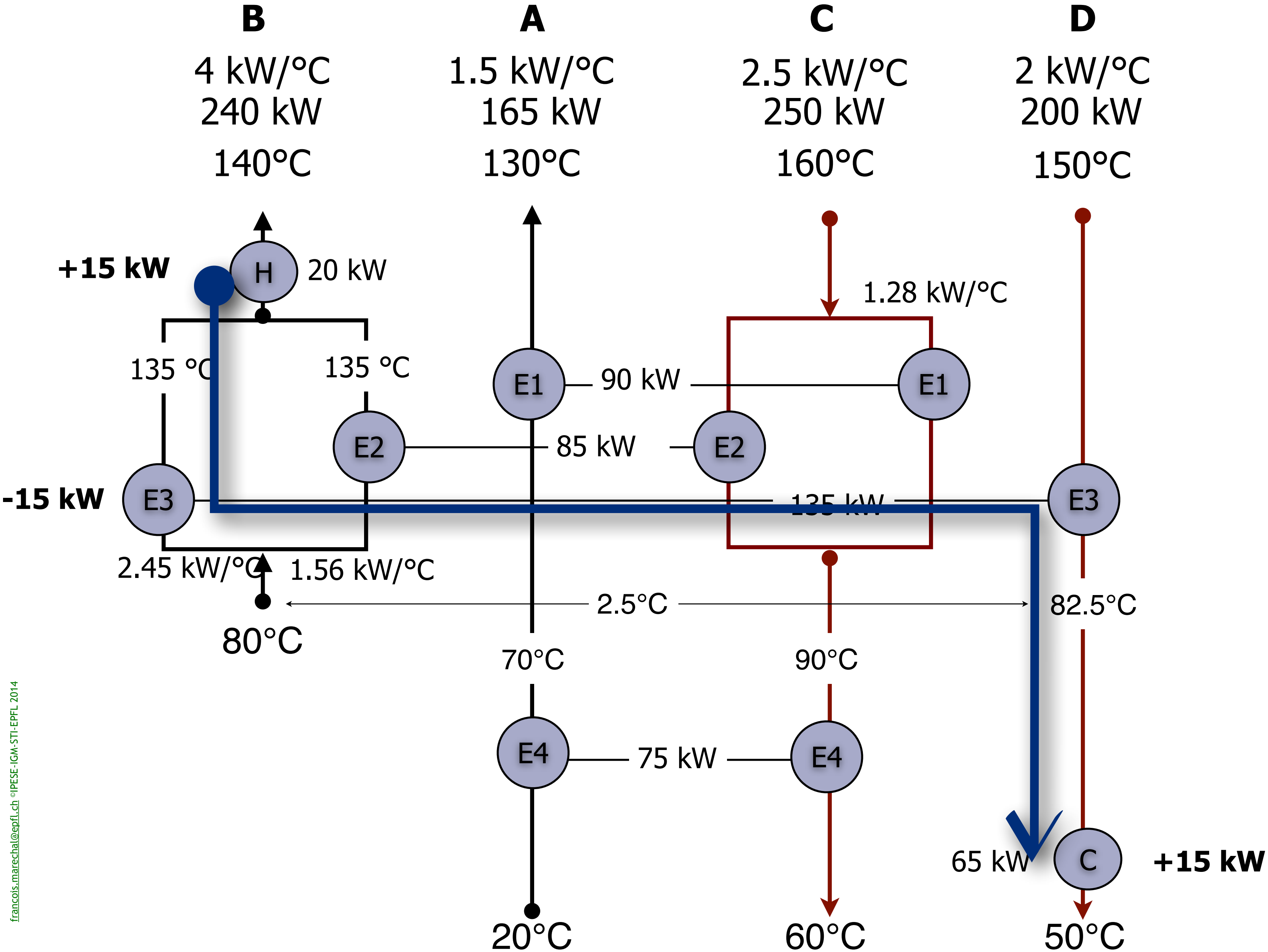
	Invest $[CHF]$	CAPEX $[CHF/year]$	OPEX $[CHF/year]$	Total $[CHF/year]$	Nb Ex.
0	173905	20340	2352	22692	7
2	190001	22222	2352	24574	6
4	**133491**	**15613**	**4118**	**19731**	**6**
5	147924	17301	4118	21419	5
6	99723	11664	16471	28135	6

Table 14: Summary of the heat exchanger network design

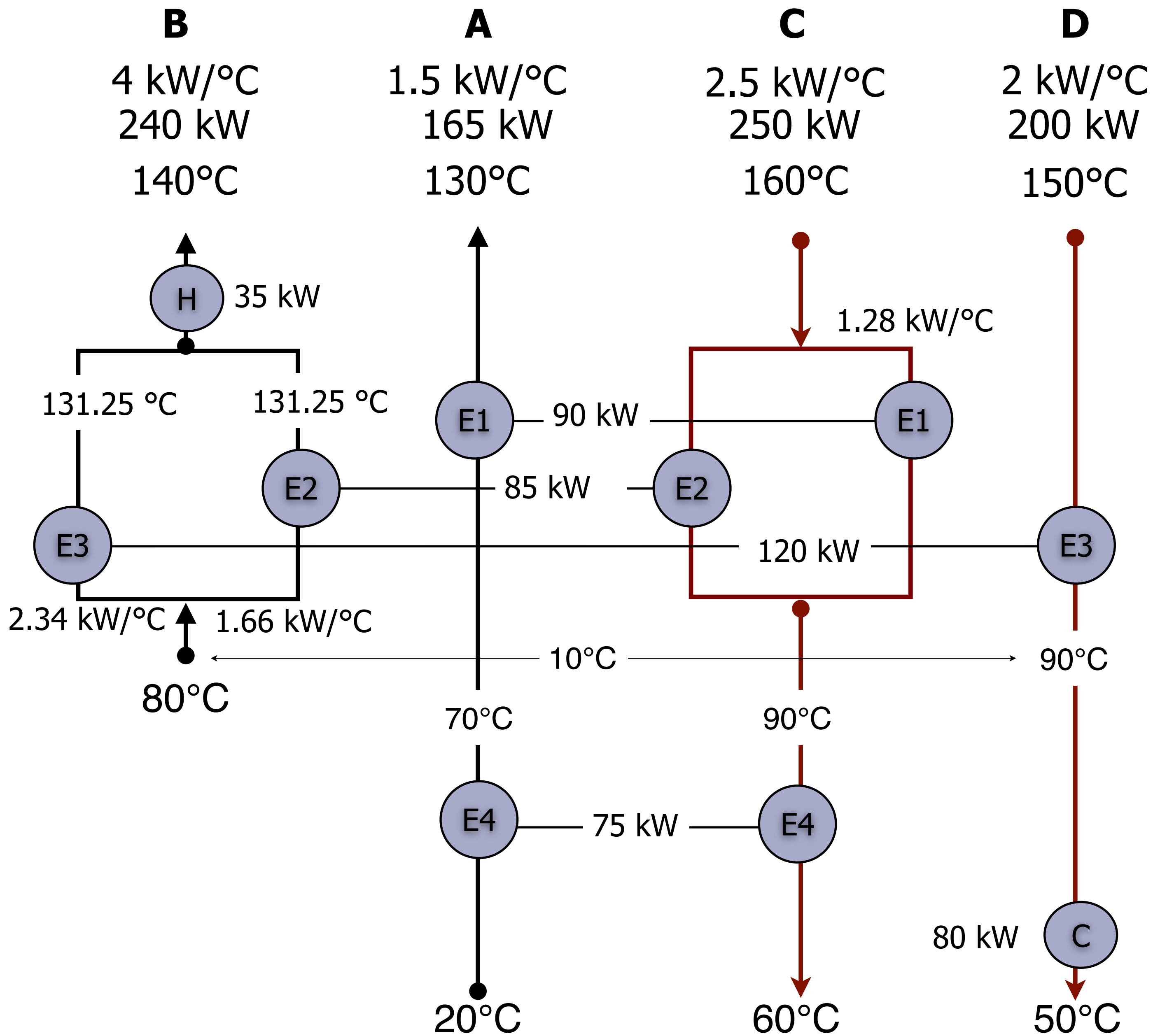
Loops : recalculate temperatures by path following



Loops + path : adjust temperature difference



Loops + path : adjust temperature difference



Calculate the heat exchangers DTmin = 10

Operating cost : 4118 CHF/year

	T_{hot} [C]	ΔT_{hot} [C]	T_{cold} [C]	ΔT_{cold} [C]	ΔT_{lm} [C]	$\dot{Q}$ [kW]	A [m^2]	Cost [CHF]
	160		90					
E1		30		20	24.66	90.0	14.6	30238
	130		70					
	160		90					
E2		28.75		10	17.75	85.0	19.1	36567
	131.25		80					
	150		90					
E3		15		2.5	13.92	120.0	34.5	55196
	131.25		80					
	90		60					
E4		20		40	28.85	75.0	10.4	23846
	70		20					
Total						360	78.6	145847

Table 10: Heat Exchangers after suppression of E5 using loop2

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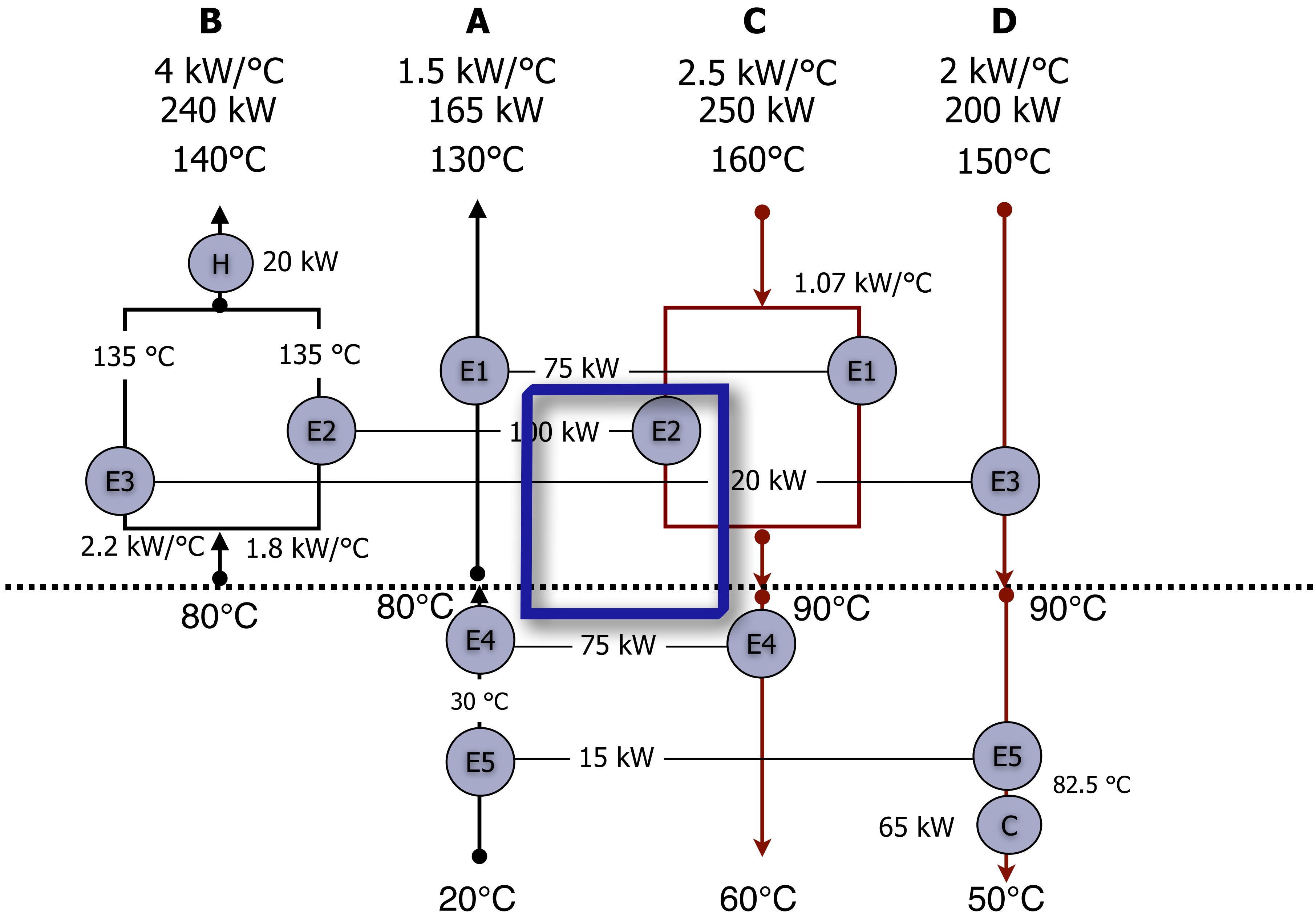
Final results : comparing solutions

	Invest $[CHF]$	CAPEX $[CHF/year]$	OPEX $[CHF/year]$	Total $[CHF/year]$	Nb Ex.
0	173905	20340	2352	22692	7
2	190001	22222	2352	24574	6
3	145847	17058	4118	21176	6
4	**133491**	**15613**	**4118**	**19731**	**6**
5	147924	17301	4118	21419	5
6	99723	11664	16471	28135	6

Table 14: Summary of the heat exchanger network design

Loops



B
4 kW/°C
240 kW
140°C
A
1.5 kW/°C
165 kW
130°C
C
2.5 kW/°C
250 kW
160°C
D
2 kW/°C
200 kW
150°C
H
20 kW
1.07 kW/°C
135 °C
135 °C
E1
75 kW
E1
E2
100 kW
E2
E3
20 kW
E3
2.2 kW/°C
1.8 kW/°C
80°C
80°C
90°C
90°C
E4
75 kW
E4
30 °C
E5
15 kW
E5
82.5 °C
65 kW
C
20°C
60°C
50°C

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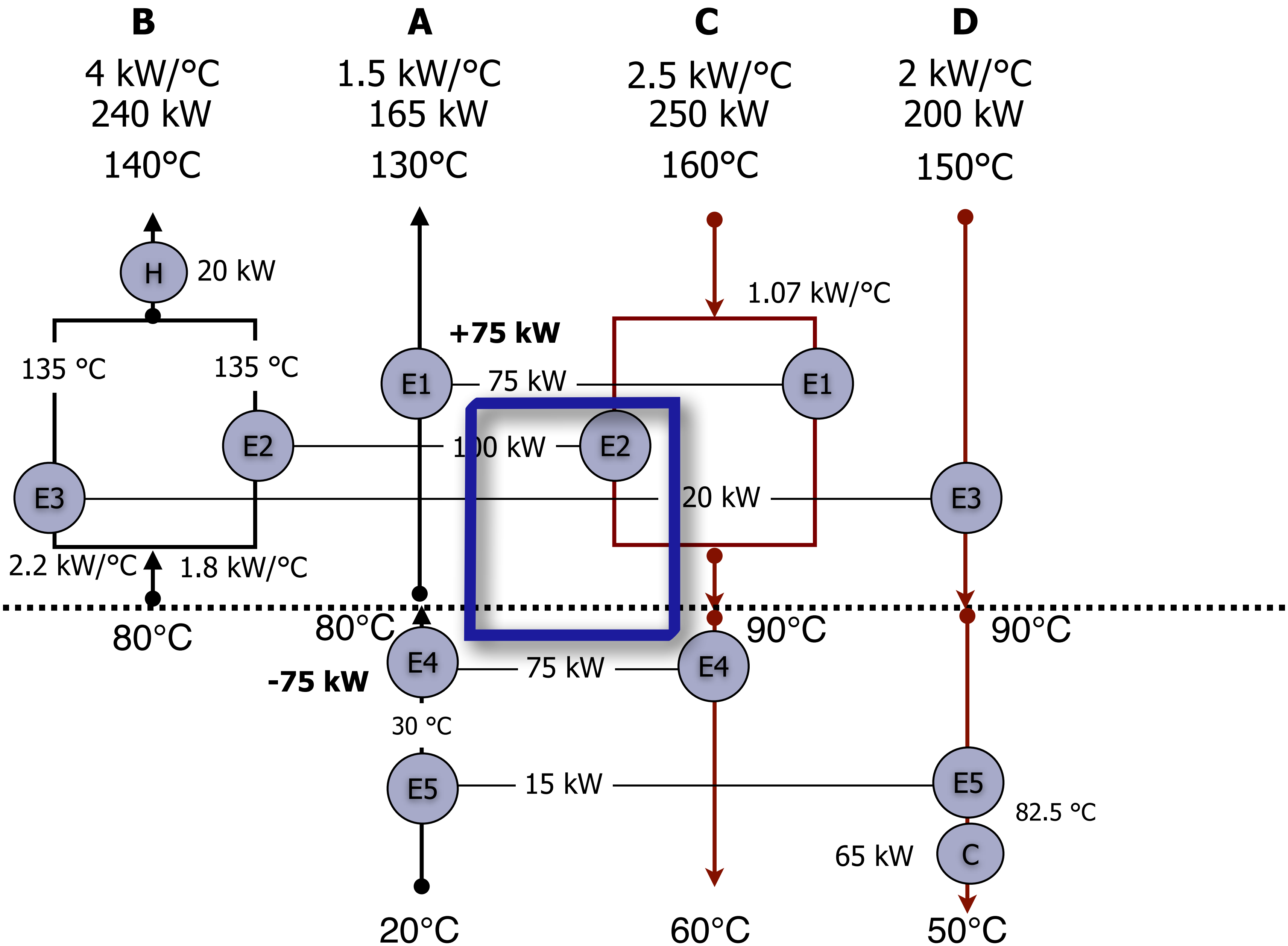
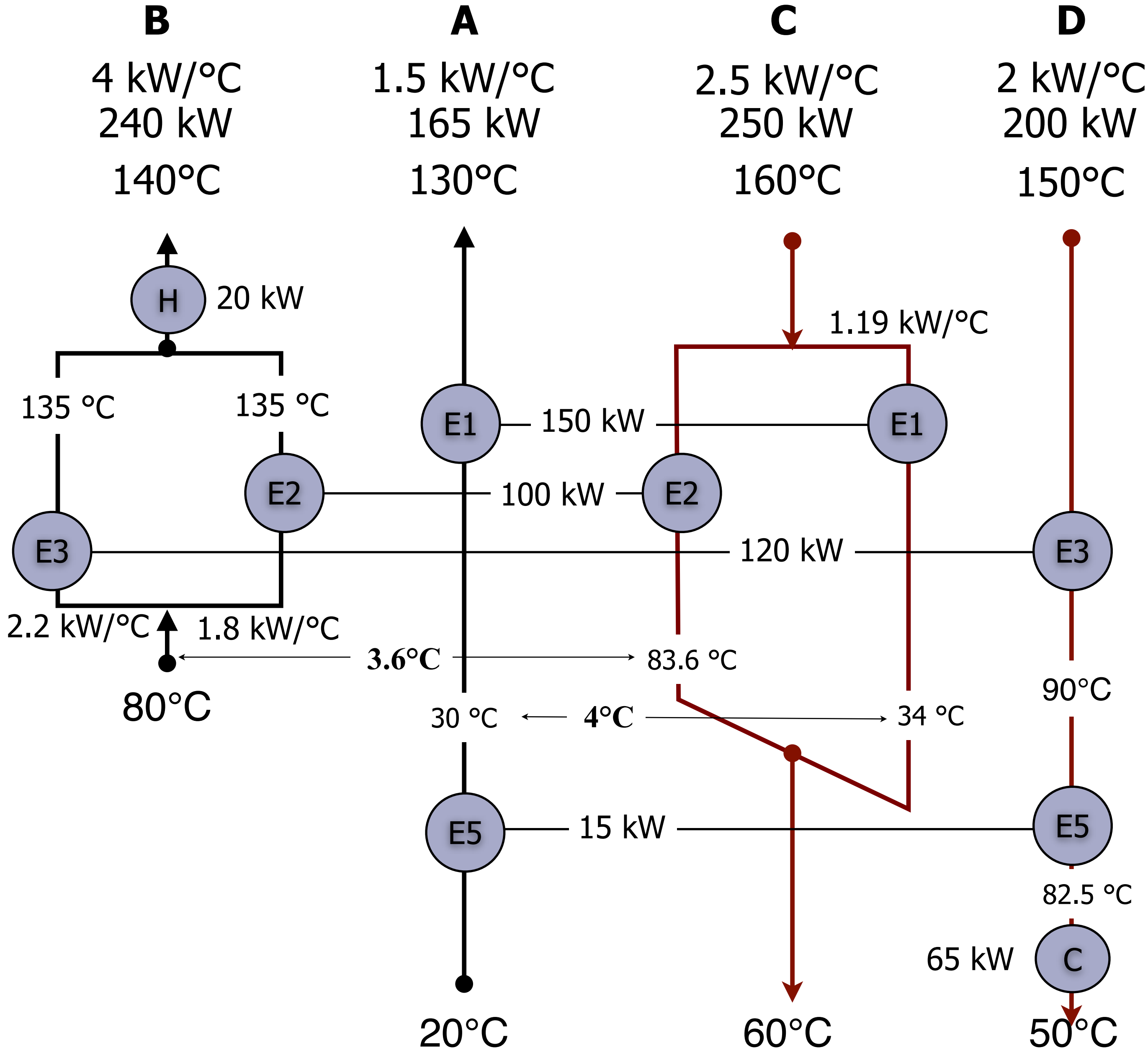
Loops


B
4 kW/°C
240 kW
140°C
A
1.5 kW/°C
165 kW
130°C
C
2.5 kW/°C
250 kW
160°C
D
2 kW/°C
200 kW
150°C
H
20 kW
1.07 kW/°C
+75 kW
135 °C
135 °C
E1
75 kW
E1
E2
100 kW
E2
E3
20 kW
E3
2.2 kW/°C
1.8 kW/°C
80°C
80°C
90°C
90°C
E4
75 kW
E4
-75 kW
30 °C
E5
15 kW
E5
82.5 °C
65 kW
C
20°C
60°C
50°C

Loops



B
4 kW/°C
240 kW
140°C
A
1.5 kW/°C
165 kW
130°C
C
2.5 kW/°C
250 kW
160°C
D
2 kW/°C
200 kW
150°C
H
20 kW
1.19 kW/°C
135 °C
135 °C
E1
150 kW
E1
E2
100 kW
E2
E3
120 kW
E3
2.2 kW/°C
1.8 kW/°C
3.6°C
83.6 °C
80°C
90°C
30 °C
4°C
34 °C
E5
15 kW
E5
82.5 °C
65 kW
C
20°C
60°C
50°C

EPFL

Recalculate the temperatures

- Operating cost : 2352 CHF/year

	T_{hot} [C]	ΔT_{hot} [C]	T_{cold} [C]	ΔT_{cold} [C]	ΔT_{lm} [C]	$\dot{Q}$ [kW]	A [m^2]	Cost [CHF]
	160		34					
E1		30		4	12.90	150.0	46.5	68043
	130		30					
	160		83.6					
E2		25		3.6	11.04	100.0	36.2	57131
	135		80					
	150		90					
E3		15		10	12.33	120.0	38.9	60055
	135		80					
	90		82.5					
E5		43.3		62.5	61.24	15.0	1.0	4630
	30		20					
Total						385.0	122.6	189859

Table 8: Heat Exchangers after loop 1 breaking to suppress E4

Final results : comparing solutions

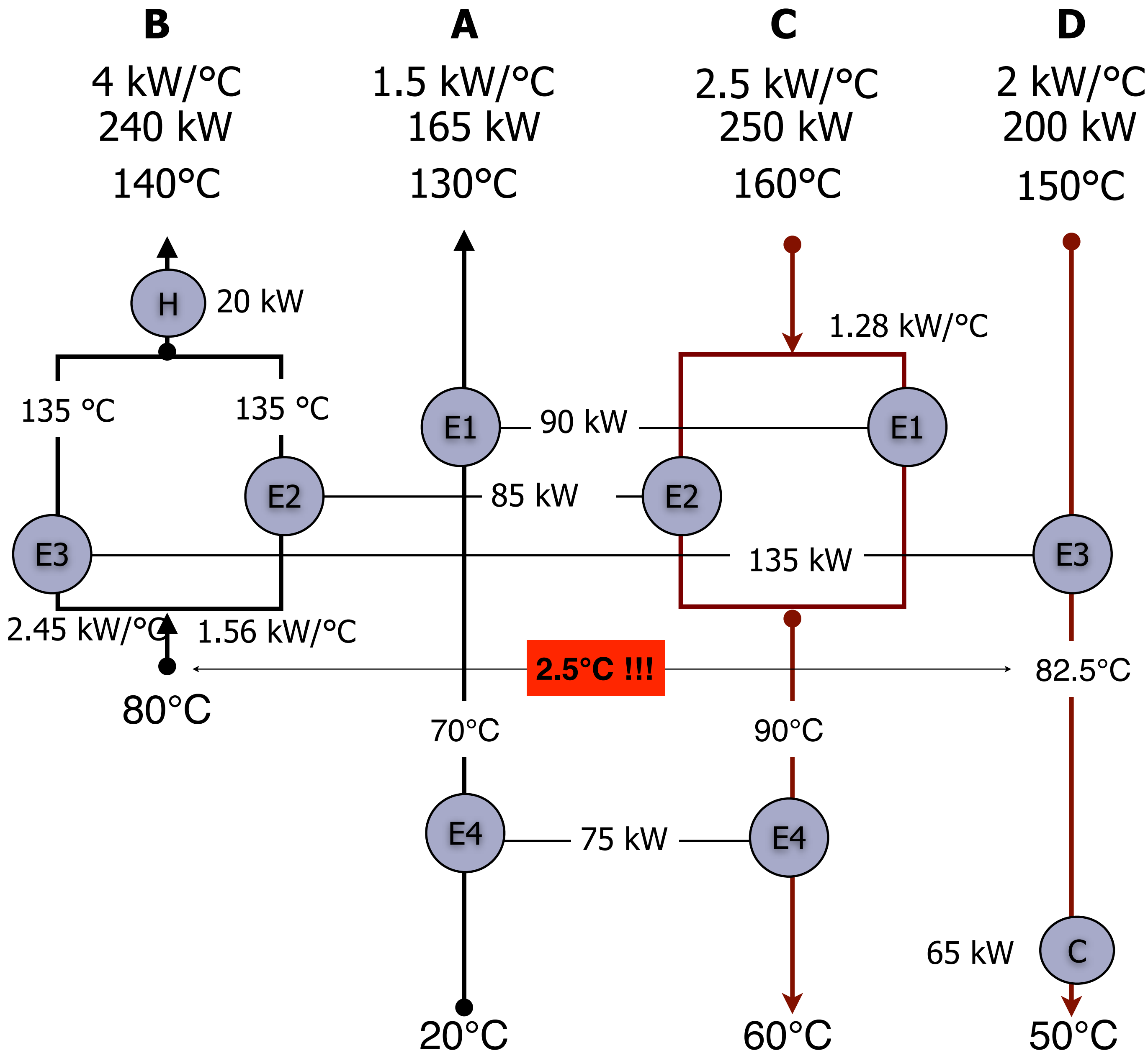
	Invest [CHF]	CAPEX [$CHF/year$]	OPEX [$CHF/year$]	Total [$CHF/year$]	Nb Ex.
0	173905	20340	2352	22692	7
1	189859	22206	2352	24558	6
2	190001	22222	2352	24574	6
3	145847	17058	4118	21176	6
4	**133491**	**15613**	**4118**	**19731**	**6**
5	147924	17301	4118	21419	5
6	99723	11664	16471	28135	6

Table 14: Summary of the heat exchanger network design

Choose the best option !

The best option is the one that has the smallest total cost. It is possible that this solution will have ΔT smaller than the ΔTmin and a smaller number of heat exchangers. This is mainly due to the fact that minimising the number of connexions does not consider the size of the heat exchangers. Smaller heat exchangers having a higher specific cost, the higher number of units can have a higher cost than a smaller number of units even if the total area is increased. It is also important to realise that at the end of the procedure, the ΔTmin is not anymore a guiding value but is a value that exist specifically for each heat exchanger.

Loops : recalculate temperatures



Optimal DTMIN for heat exchangers

- **Two different values of DTmin**
  - HRAT (Heat Recovery Approach Temperature)
    - Used to compute energy targets
    - 1 single value for the system level
    - independent of the HEN structure
    - Used to identify pinch point
  - $EMAT_i$ (Exchanger Minimum Approach Temperature)
    - Used for the optimal use of the heat exchangers
    - for each heat exchanger $EMAT_i \geq \mathbf{EMAT} \qquad \forall i \in \{\text{Heat Exchangers}\}$
    - HEN structure dependent
    - Optimal Heat exchanger area usage