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A knowledge-based system for low-grade waste heat recovery in the process industries

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Abstract

The rising cost of energy, combined with increasingly stringent legislation to reduce greenhouse gas emissions is driving the UK process industries toward increasing energy efficiency. Significant gains can be made in this sector by recovering low-grade waste heat as up to 14TWh per annum (4% of total energy use) of the UK process industries' energy consumption is lost as *recoverable* waste heat. Substantial recovery of this would have economic benefits of the order of £100s of million/year and environmental benefits of 100s of thousands of tonnes of carbon dioxide equivalent per year. A similar situation is envisaged in other industrialised countries.

This paper describes the development of a knowledge-based system for the selection and preliminary design of equipment for low-grade waste heat recovery in the process industries. The system processes commonly available plant data to select the most appropriate technology for waste heat recovery from a range of programmed options. Case-study testing shows that the system can successfully select and design viable solutions for waste heat recovery from a range of options, producing designs which are economically, environmentally and technically feasible.

Key words

Waste heat recovery; Low-grade waste heat; Knowledge-based systems; Heat exchanger; Heat pump; Organic Rankine cycle.

Nomenclature and Abbreviations

Cp	Specific heat capacity (kJ/kgK)
m	Mass flow (kg/s)
P	Pressure (Pa)
T	Temperature (^{o}C)
η	Efficiency (%)
μ	Viscosity (Pa.s)
ρ	Density (kg/m^3)
HEx	Heat exchanger
HP	Heat pump
KB	Knowledge-base

KBS	Knowledge-based system
N/A	Not applicable
ORC	Organic Rankine cycle
WHR	Waste heat recovery

1. Introduction

Energy use in industry is becoming increasingly scrutinised for a variety of reasons. Firstly, the rising cost of both electricity and fossil fuel resources is leading to ever-increasing utility expenditure which can be a severe constraint in the current uncertain financial climate. Secondly, government legislation often inflicts ambitious targets for greenhouse gas reduction, such as the Climate Change Act of 2008 [1] in the UK which aims for an 80% reduction in greenhouse gas emissions between the years of 1990-2050.

Significant gains can be made in these areas by recovering low-grade waste heat (<260^{o}C [2]). Reay and Morrell [3] surveyed the potential for low-grade waste heat recovery (WHR) and found that 11.4TWh of *recoverable* waste heat is emitted to the environment in the UK processing sector. McKenna and Norman [4] used a spatial modelling technique to predict the potential for low-grade waste heat recovery and found it to be 14.4TWh, a reasonable agreement with the prediction of Reay and Morell. Law *et al* [5] estimated that the potential cost savings for waste heat recovery (via reduction in utility bills) was up to £285m/year and the potential greenhouse gas reductions were up to 2093ktCO_2eq/year depending on the methods of waste heat recovery employed.

Methods for identifying potential heat sources for waste heat recovery and heat integration are well established, beginning with the work of Linhoff *et al* [6] who originally suggested the concept of PINCH methods for heat integration. These ideas have been further researched to incorporate complex algorithms for matching of sources and sinks [7], batch processing [8], heat pumps [9] and “cross-border” integration [10].

Various software packages have also been created utilising the pinch methodology including the EINSTEIN expert system [11] which also incorporates renewable primary energy sources, the GREENFOODS [12] package which specifically targets the food sector and large commercial packages such as the Aspen Energy Analyser [13].

However, little work has been done in the area of specific equipment selection. Heat integration methods are almost exclusively based on waste heat recovery via shell-and-tube heat exchanger with no consideration of process conditions or optimal heat exchanger design. Furthermore, pinch methods which have been modified to include heat pumps *etc* do so only on an energy balance basis, and do not consider practical aspects of design such as working fluid selection.

There is some existing literature discussing the benefits and drawbacks of various waste heat recovery methods. For example, Law *et al* [4] discuss methods of WHR in the UK food industry, Amon *et al* [14] discuss WHR in the Californian tomato paste industry, Ammar *et al* [15] discuss WHR in the UK process industries and Hammond & Norman [16] discuss WHR in UK industry. However, while papers such as these can provide an indicative assessment of overall potential for utilisation of WHR equipment, such an analysis cannot accurately identify site-level opportunities. Hence, individual case-studies must be addressed by somebody with suitable knowledge of WHR technology, most commonly a consulting engineer.

Furthermore, confusion often exists regarding selection of the *most appropriate* WHR equipment when, superficially, two or more options appear to be equally suitable. This is particularly problematic when complex solutions such as organic Rankine cycles are required. For example, Law *et al* [17] discuss the relative merits of high temperature heat pumps and organic Rankine cycles for waste heat recovery in the chemicals industry, and Walsh and Thornley [18] who discuss the merits of a waste heat boiler and an organic Rankine cycle for WHR in the coke industry. In both cases, the *final* decision regarding which technology is more suitable is dependent on the aims of the individual site in question, and no over-riding theme is present.

This paper presents the development of a knowledge-based system (KBS) for low-grade waste-heat recovery in the process industries with a specific focus on the non-bias selection of the most appropriate equipment on an individual case-study basis. The system operates as follows (also depicted in Figure 1):

1. User identifies waste heat source and potential waste heat sink (if available)
2. User inputs data for waste heat source, heat sink (if available) and general plant data
3. System selects *available* methods of waste heat recovery (*i.e.* methods which are both technically feasible and meet the needs of the plant)
4. System produces preliminary design of *available* equipment, including economic and CO_2 reduction data
5. *Available* equipment is ranked according to user-defined specification (capital cost, payback time or CO_2 reduction)

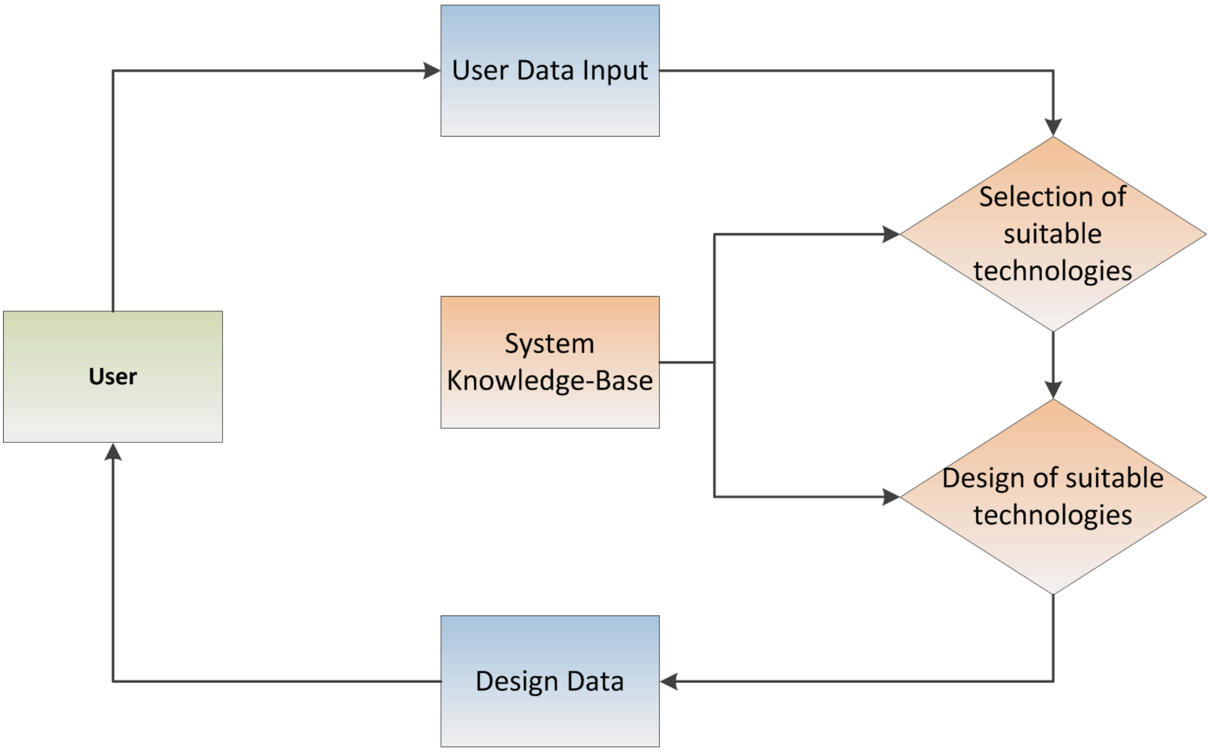

Figure 1. Basic schematic of the knowledge-based system

The system aims to provide a non-bias consultancy tool for use in the preliminary assessment of waste heat recovery technology in the process industries. It is hoped that the system will encourage the uptake of WHR projects by removing the confusion and need for expert consultancy from the preliminary assessment of equipment suitability.

2. Methodology

2.1 Equipment data base

The knowledge-base (KB) of equipment is selected according to the following scope:

1. The system must include a variety of waste heat recovery techniques: *i.e.* options for heat transfer, heat conversion and heat upgrade in order to accommodate a wide-range of possible scenarios
2. The system must include technologically viable results: *i.e.* only include technologies which have been proven on an industrial scale
3. The system must only include economically viable results: *i.e.* only include technologies which have been proven to show acceptable pay back periods (less than 5 years)

Table 1 below shows the equipment selected for inclusion in the KB.

Table 1. Summary of technologies included in the equipment data base

Name	Classification

Various heat exchangers	Direct heat transfer from source-to-sink
Heat Pump (vapour compression)	Heat upgrade to a more desirable temperature before transfer to sink
Organic Rankine cycle	Heat conversion to electricity

Table 2 expands on the various types of heat exchangers included in the system and provides data and a brief discussion on their limitations. Tables 3 and 4 show data and a brief discussion of the limitations of the heat pump and the organic Rankine cycle. The data is adapted from various sources including [19-23].

Table 2. Summary of the limitations of the various types of heat exchangers included in the system knowledge-base

Technology	Max. temperature	Max. pressure	Typical materials of construction	Phases	Access for cleaning?	Corrosion resistance	Fouling considerations	Max Viscosity	Max Solid Particle Size	Cross contamination considerations
	ºC	bar						CP	mm	
Brazed plate	225	30	Stainless steel, titanium; copper brazing	Liquid, liquid boiling, condensing vapour	No: fully brazed	Good: via coatings	Cannot accommodate solid particles in feeds	1000	N/A	No issue
Finned-tube	>260; Fin-side must not exceed 200	Shell 300; Tubes 1400	Stainless steel, titanium; fins aluminium or copper; shell may be in carbon steel; many others	Tube-side: Liquid, liquid boiling, condensing vapour Shell-side: Gas, humid gas	Yes: on tube side (remove bundle to clean)	Good: via coatings	Can accommodate fouling fluids on the tube-side & and light fouling on air-side	3000	15	No issue
Gas-gas plate	150 (aluminium); >260 (stainless steel)	16 Max. pressure difference between streams: 1.05	Stainless steel, aluminium	Gas, humid-gas condensation can be tolerated via use of drip tray	Yes: via gaskets	Poor: not commonly coated to prevent corrosion	Can accommodate light fouling on both sides	N/A (gas phase only)	N/A	No issue
Gasketted plate	180	16	Stainless steel, titanium	Liquid, liquid boiling, condensing vapour	Yes: via gaskets	Good: via coatings	Can accommodate light fouling on both sides	1000	2	No issue
Plate and shell	>260	100	Stainless steel, titanium; shell may be in carbon steel	Liquid, liquid boiling, condensing vapour	No: fully welded	Good: via coatings	Cannot accommodate solid particles in feeds	8	1	No issue

Rotary regenerator	>260	Normally around ambient. Max. pressure differential between streams: 1.06	Aluminium, Ceramics, Polymers	Gas	Yes, although can be configured to promote self-cleaning	Good: can be manufactured by a variety of materials	Can tolerate light fouling as can be configured to promote self-cleaning	N/A (gas phase only)	N/A	Up to 5%
Run-around-coil	200; Fins must not exceed 200	75	Stainless steel; aluminium or copper fins	Gas, humid-gas condensation can be tolerated via use of a drip-tray	Yes, via gaskets	Good: via coatings	Can tolerate light fouling as coils can be mechanically cleaned	N/A (gas phase only)	N/A	No issue
Shell and tube	>260	Shell 300; Tubes 1400	Stainless steel, titanium; shell may be in carbon steel amongst many others	Liquid, boiling liquid, condensing vapour, gas	Yes: on tube side (remove bundle to clean)	Good: via coatings	Can accommodate fouling fluids on the both sides	3000	15	No issue
Spiral plate	>260	30	Carbon steel, stainless steel, titanium	Liquid	Yes: via gaskets, although flow regime encourages scouring of fouling layer	Good: via coatings	Can accommodate fouling fluids on both sides	>1000	20	No issue
Welded plate	>260	40 fully welded; 16 on gasketted side if semi-welded	Stainless steel, titanium	Liquid, liquid boiling, condensing vapour, gas (welded side)	Yes: may be partially welded to allow access on one side via gaskets	Good: via coatings	Can only accommodate solid particles/fouling on the gasketted-side if	1000	N/A	No Issue

							unit is semi-welded			

Table3. Summary of the limitations of the heat pumps included in the system knowledge-base

Technology	Max. Condenser Temperature	Typical Pressure Ratio	Typical Corresponding Temperature Lift	Phases	Design Notes	Working fluids included
	°C					
Vapour compression closed cycle	140 (working fluid dependant)	2.8 (based on centrifugal compressor)	Around 40	All (dependant on heat exchangers)	N/A	R134a, R717 (ammonia), R245fa, R600
Mechanical vapour recompression (open cycle)	Generally around 120	1.25 - 2.5 (dependant on compressor type)[3]	5-25	Water vapour source; boiling water heat sink	Existing units most commonly use internal heating coils or an external heat exchanger; New MVR design may require a new heat exchanger or may aim to re-use existing unit	N/A

Table 4. Summary of the limitations of the power generation options included in the system knowledge-base

Technology	Minimum Reported Source Temperature	Max. Evaporator Temperature	Typical Min. Condenser Temperature	Heat Source Phases	Process Limitations	Typical Heat Sinks	Working fluids included
	°C	°C	°C				
Organic Rankine cycle	73	140	11	All (dependant on heat exchangers)	Heat source must be continuous, not intermittent	Water, Air	R134a, R245fa, R600

2.2 Data required

The specification of the data input to the system was crucial as it must trade-off between the requirements for accurate results to be calculated and the expected time constraints of the target end-user (an industrial process engineer). Table 5 below summarises the quantitative source/sink data required by the system, Table 6 summarises the qualitative source/sink data required by the system, and Table 7 summarises *general* plant data required for economic and environmental analysis of proposed solutions.

Heat transfer coefficient data for the heat sources/sinks is pre-programmed from various sources such as [19], [20] and [24] into the system and are “looked-up” based on the fluid properties and nature described by the data in Tables 5 and 6. This is because it is assumed that this data would not be readily available to an industrial energy. Hence, it removes a time-consuming step from the system usage. Furthermore, using assumed values of heat transfer coefficients is *generally* deemed acceptable in the production of preliminary designs, which is one of the outputs from the KBS (as opposed to a final, optimised design).

Table 5. Quantitative source/sink data required for KBS operation

	Symbol (units)
Source phase	N/A
Sink phase	N/A
Source mass flow rate	m_{source} (kg/s)
Sink mass flow rate	m_{sink} (kg/s)
Source temperature	T_{source} (^oC)
Source target temperature	$T_{source,target}$ (^oC)
Sink temperature	T_{sink} (^oC)
Sink target temperature	$T_{sink,target}$ (^oC)
Source specific heat capacity	$C_{p,source}$ (kJ/kg.K)
Sink specific heat capacity	$C_{p,sink}$ (kJ/kg.K)
Source pressure	P_{source} (kPa)
Sink pressure	P_{sink} (kPa)
Source density	ρ_{source} (kg/m^3)
Sink density	ρ_{sink} (kg/m^3)
Source viscosity	μ_{source} (kg/m.s)
Sink viscosity	μ_{sink} (kg/m.s)

Table 6. Qualitative source/sink data required for KBS operation

	Notes
Source solid content and nature	Data required here includes the mass fraction of solids in the stream, the nature of the solids and the average particle diameter
Sink solid content and nature	

Source fouling tendency	This is heavily linked to the source solid content although other types of fouling are noted such as scaling. It is difficult to definitively quantify fouling for every case study and this remains subjective
Sink fouling tendency	
Source corrosivity	This is linked to both the source/sink properties and the materials of construction
Sink corrosivity	
Source material compatibility	This is heavily linked to the corrosivity of the two fluids. Some heat exchangers may only be constructed from certain materials, hence this influences heat exchanger selection
Sink material compatibility	
Source access for maintenance/cleaning	This is heavily linked to both corrosivity and fouling characteristics, *i.e.* if fluid(s) is (are) fouling and/or corrosive then access will be required
Sink access for maintenance/cleaning	

Table 7. Plant data required for KBS operation

	Symbol (units)
Current method of heating sink	N/A
Efficiency of current method of heating sink	η (%)
Utility costs	N/A (£/kWh)
Utility associated emissions	N/A (tCO_2eq/kWh)
Plant hours of operation	N/A (h/year)

2.3 System equipment selection

The selection of equipment by the KBS is completed on two levels, as a consulting engineer would tackle such a problem. The first level, is relatively simple and addresses the availability of potential heat sinks and the aims of the plant in question. Here, simple statements are considered, for example:

- **IF** a "matching" heat sink is NOT available **THEN** one may not use a heat exchanger.
- **IF** a heat sink within a reasonable temperature lift (~40K) is NOT available **THEN** one may not use a heat pump.
- **IF** the plant has no interest in electricity generation **THEN** one may not use an organic Rankine cycle

Such statements can be extended to consider the various types of heat exchangers included in the system, for example, thereby creating logic such as:

- **IF** a “matching” heat sink is available **AND** heat source is in the liquid phase **AND** heat sink is in the liquid phase **THEN** one may use a liquid-liquid heat exchanger. (Note: the selection of which types of liquid-liquid heat exchanger are suitable is then considered in level 2 of the selection logic)

Figure 2 overleaf shows the level 1 technology selection logic displayed in decision tree format. Figure 3 shows a continuation of the heat exchanger level 1 selection logic in order to select which heat exchanger category is required based on the phase of the heat source and sink.

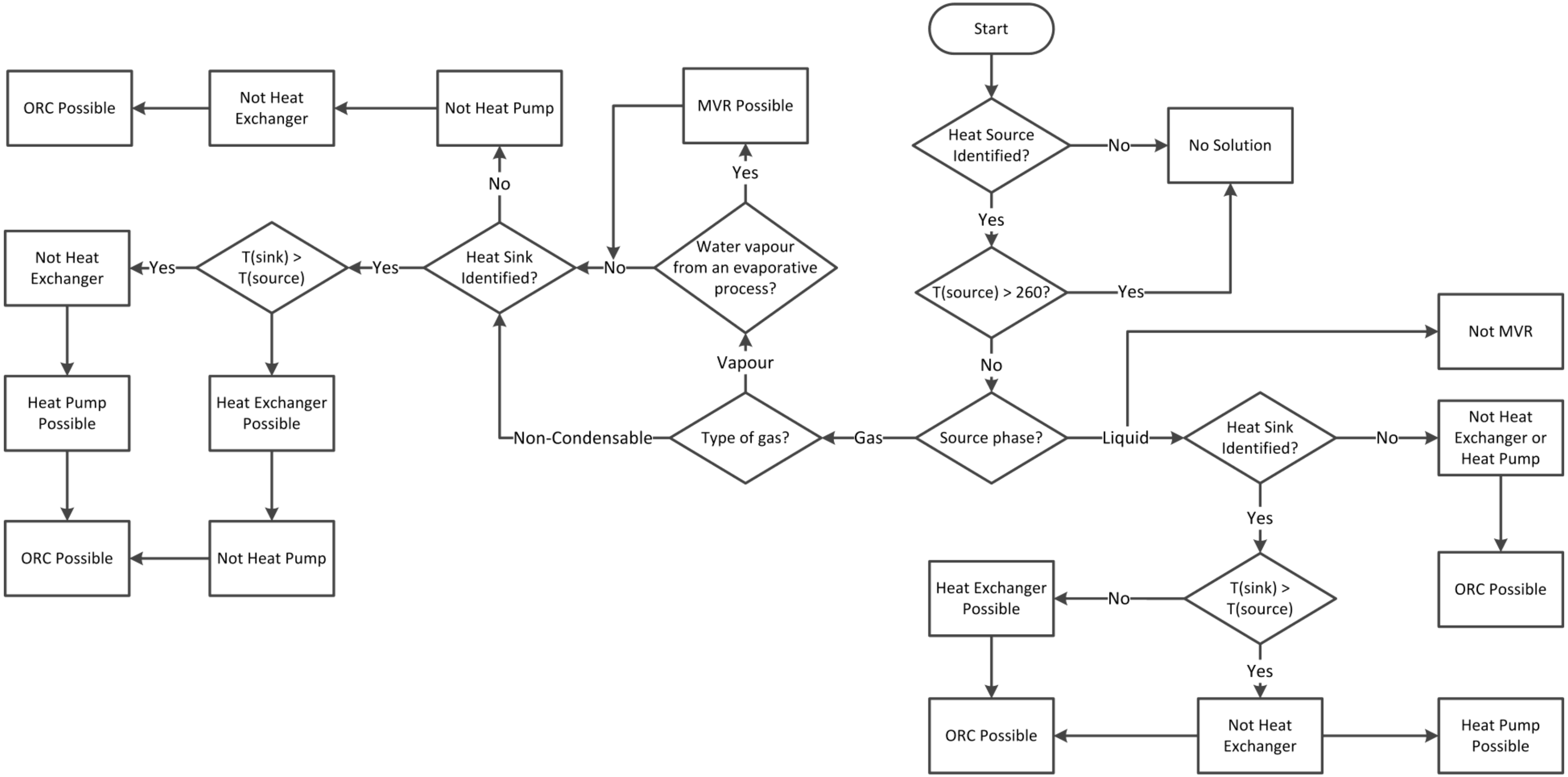

Figure 2. Level-1 selection logic of KBS

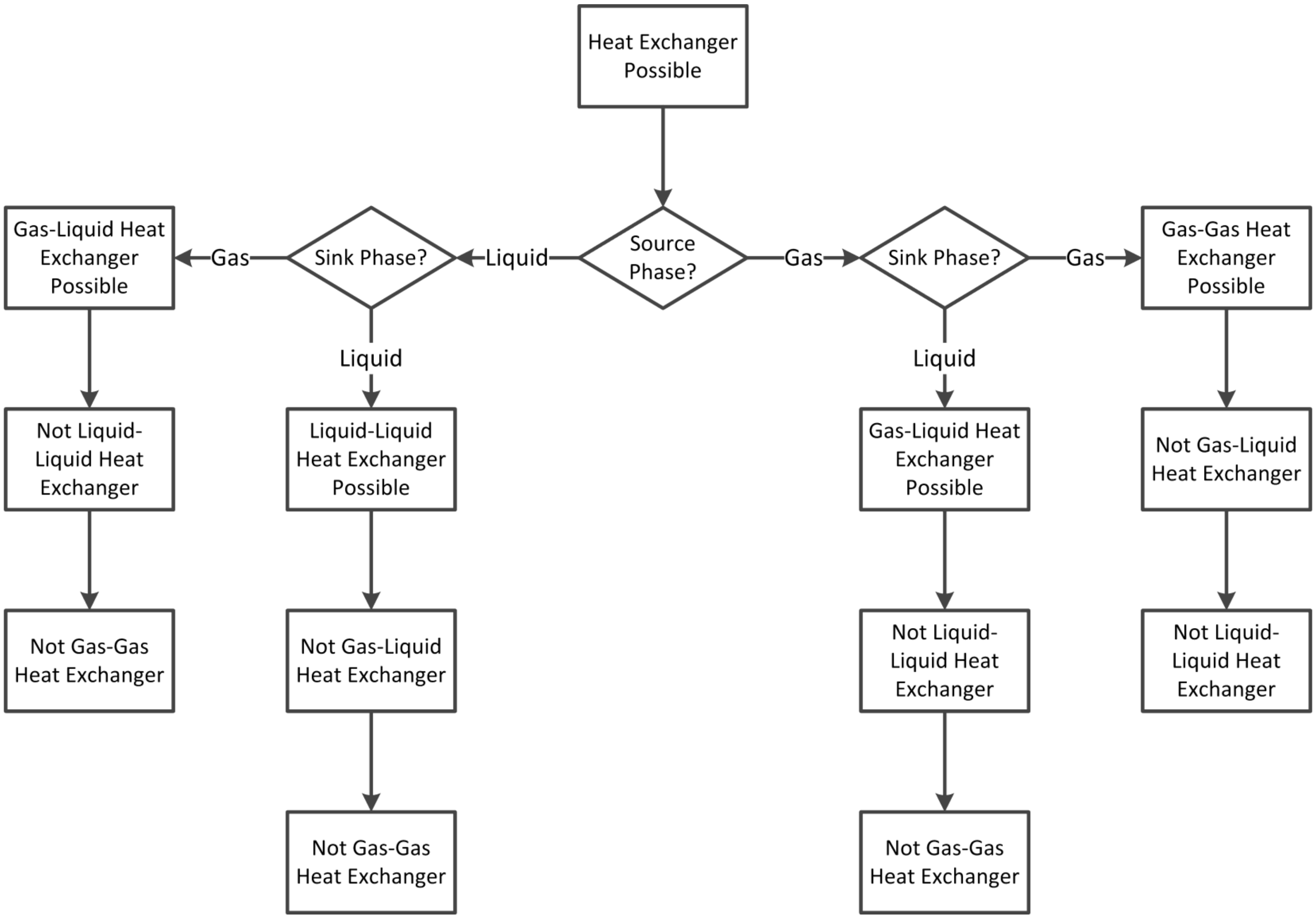

Figure 3. Extension of leve-1 of KBS selection logic to determine the category of heat exchanger required

The next stage in selection of the available technologies for waste heat recovery is more complex and is based on the technological limitations of the equipment chosen for inclusion in the knowledge-base.

This is split into five modules corresponding to the five general categories of heat recovery technology included in the system knowledge base: gas-gas heat exchangers, gas-liquid heat exchangers, liquid-liquid heat exchangers, heat pumps (MVR and closed cycle) and organic Rankine cycles. Each module contains decision-tree-type selection procedures based on the technological limitations of teach type of system (for example, according to the data displayed in Tables 2, 3 and 4).

Unfortunately, the flow-diagrams are too large for publication in this journal. Figure 4 below shows a short section of the liquid-liquid heat exchanger selection knowledge-base, and Figure 5 below shows a section of the heat pump working fluid selection knowledge-base. A larger section of the liquid-liquid heat exchanger selection knowledge-base is available as a supplementary file on the journal website, while full decision tree diagrams (for the entire system) may be viewed in the thesis by Law [25].

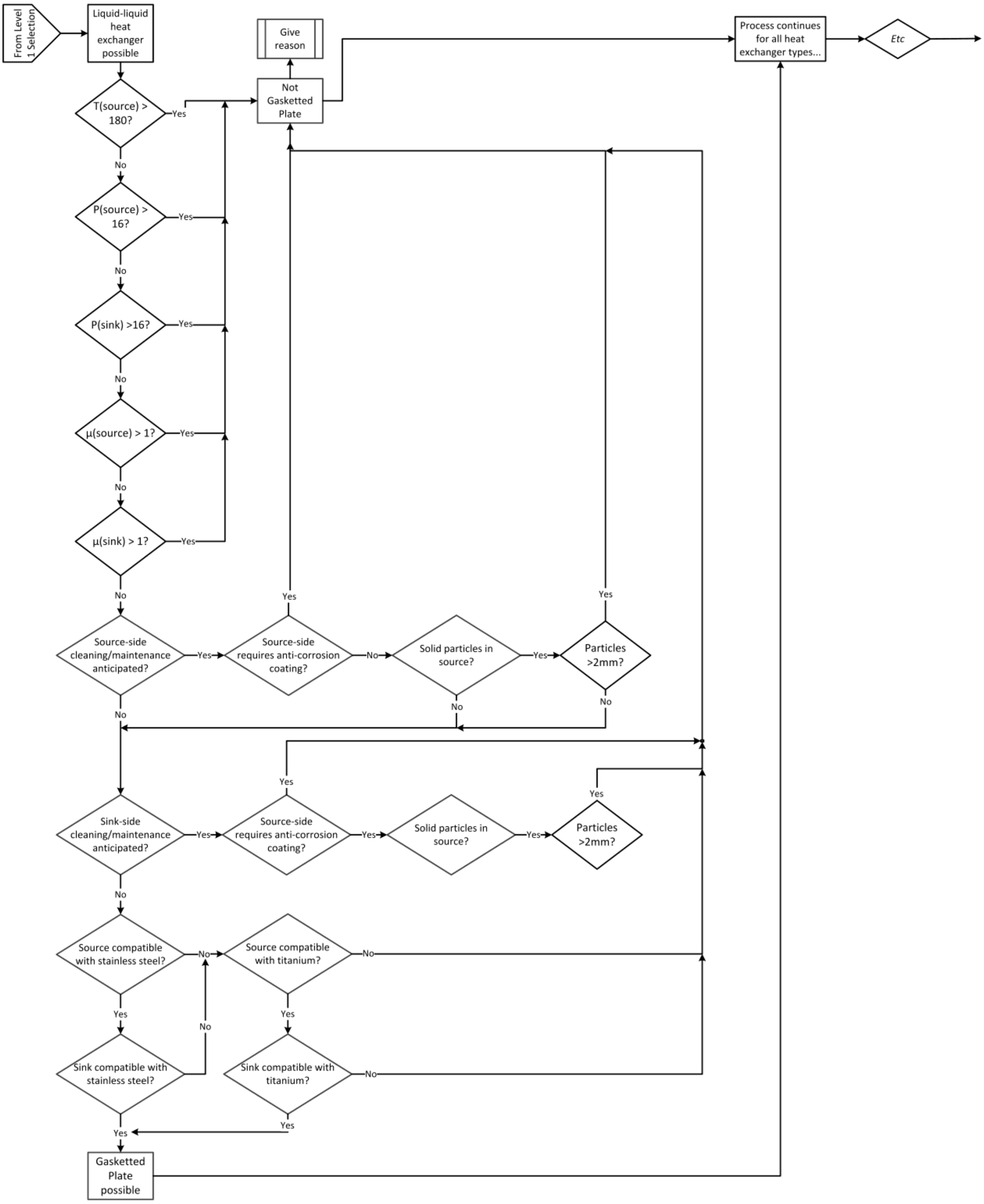

Figure 4. Section of the liquid-liquid heat exchanger selection knowledge-base

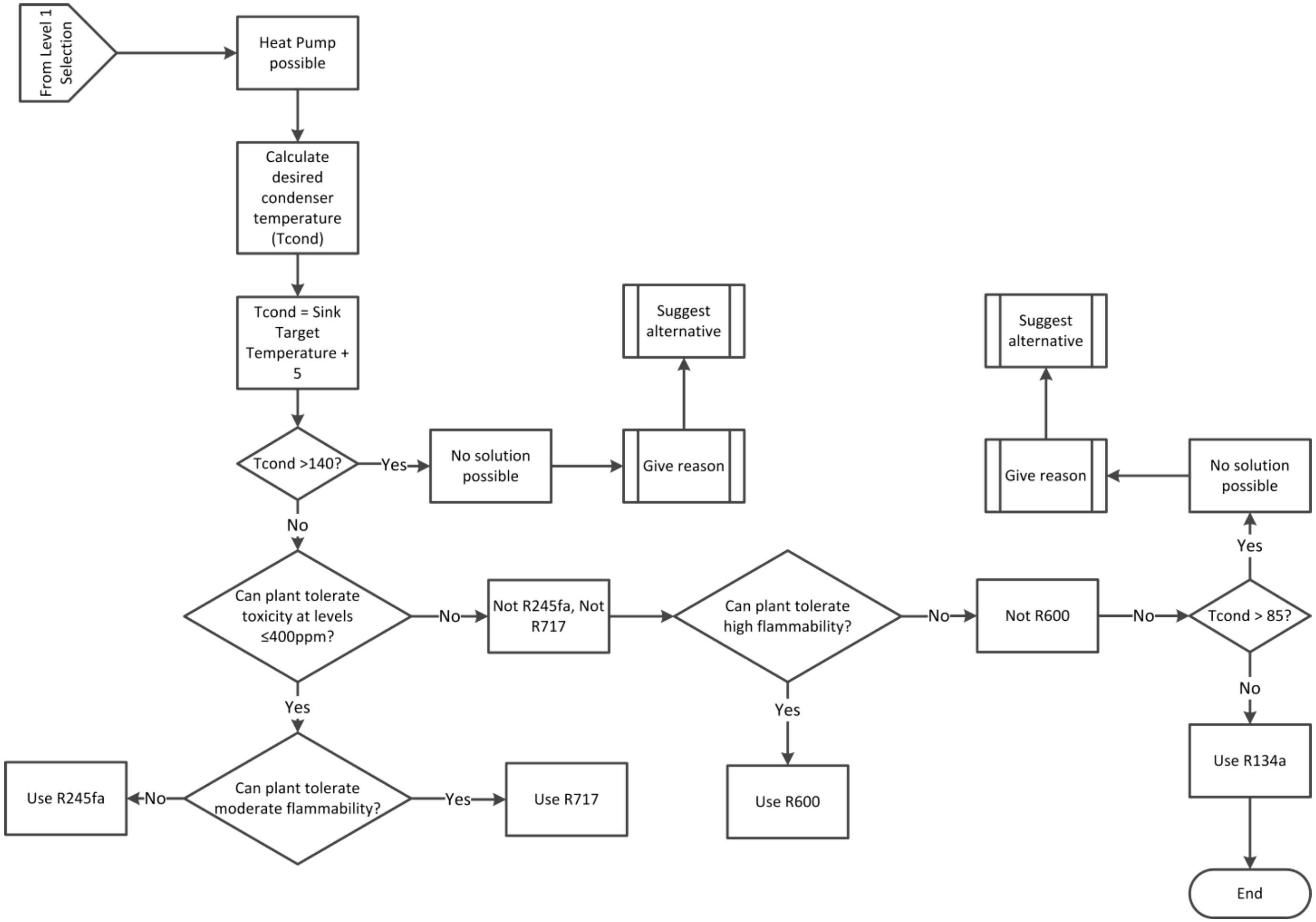

Figure 5. Section of the heat pump working fluid selection knowledge-base

Following stages 1 and 2 of the selection process, the equipment available for use (based on plant and technological limitations) are selected. Final decision and ranking of the options is based on the preliminary design described below.

2.4 System equipment preliminary design and ranking

Preliminary equipment design is carried out using *standard* methods as described in common texts such as [19], [20], [22], [24] and [26]. Table 8 below summarises the design equations and methods employed for the various technologies included in the database. Again, full decision-tree-type diagrams of the design and optimisation steps are too large to include in this paper but are available in the thesis by Law [25].

Table 8. Summary of design methodologies employed by system

Heat Exchanger	Log mean temperature difference (LMTD) method or effectiveness method depending on the type of heat exchanger and the data available. Heat exchanger components (for example, tube sizes in shell and tube, and plate sizes in plate heat exchangers) are selected from a database of *standard* sizes in the system knowledge-base. Estimate heat transfer coefficient and max. effectiveness data taken from a variety of sources including [19], [20] and [22]
Heat Pump	Standard steady-state models for each component are used along with iterative heat balance calculations for each of the heat exchangers. Data and equations taken from common engineering texts such as [22], [21] and [26]
Organic Rankine Cycle	Standard steady-state models for each component are used along with iterative heat balance calculations for each of the heat exchangers. Data and equations taken from common engineering texts such as [22], [21] and [26]

Table 9 below summarises the output results from the system. Each technology can then be ranked according to which result is critical to the plant in question.

Table 9. Summary of the output results from the system

Size of units (kW)	Based on methods described in Table 8
Physical dimensions (m)	Based on methods described in Table 8

Capital cost (£GBP)	Based on cost factor and/or manufacturer data when available from sources such as [19], [20] and [27]
Utility savings (kWh)	Based on the duty of the waste heat recovery system and the efficiency of the current heating method (where applicable)
Potential cost savings (£GPB/year)	Based on utility savings and local utility prices (note: any utility expenditure is accounted for)
Potential greenhouse gas emissions savings (tCO_2eq/year)	Based on utility savings and local associated emissions (note: any utility expenditure is accounted for)
Efficiency/Effectiveness/COP/Thermal efficiency (depending on type of equipment)	Based on methods described in Table 8
Inlet and outlet temperatures; Inlet and outlet pressures; Source/sink pressure drop; Cycle stream temperature and pressure (depending on type of equipment)	Based on methods described in Table 8

2.5 Programming

The system is written in the Java language and compiled using the Java development kit version 7 [28].

3. Testing and Discussion

The system is tested using case study data from the textiles industry. The data is taken from the paper by Pulat *et al* [29] where waste heat recovery was considered from a *typical* hot effluent stream (note: further case study testing is shown in the thesis by Law [25]). The waste heat source is defined as an approximately steady-state supply of spent process water from processes such as bleaching, washing and dyeing, via a buffer tank. The heat sink is the feed to the hot water store. The data input to the KBS is summarised in Table 10.

Table 10. Data input to KBS (adapted from Pulat *et al* [29])

Source Nature	Liquid (waste water)
Source Temperature (^{o}C)	83.0
Source Target Temperature (^{o}C)	20.0[1]
Source Mass Flowrate (kg/s)	8.33
Source Pressure (bar)	1.01
Insoluble solids in source	No
Source Viscosity (Pa.s)	0.001[2]
Source Density (kg/m^3)	1000[2]
Source Material Compatibility	Only Stainless Steel
Source Access for Cleaning Required	Yes

Sink Nature	Liquid (water)
Sink Temperature	20.0
Sink Target Temperature	60.0
Sink Mass Flowrate (kg/s)	12.1
Sink Pressure (bar)	4.00
Insoluble Solids in Sink	No
Sink Viscosity (Pa.s)	0.001
Sink Density (kg/m^3)	1000
Sink Material Compatibility	No constraints listed (source limiting)
Sink Access for Cleaning Required	Yes (scaling possible)
Current Heating Utility	Gas
Efficiency of Current Heating Method	Assumed in paper to be 100%
Cost of Gas (£/kWh)	0.022[3]
Cost of Electricity (£/kWh)	0.079[3]
Operating hours/year	7200
Plant tolerant to working fluids with toxicity levels of less than or equal to 400 ppm by volume	Yes[4]
Plant tolerant to working fluids with high or moderate flammability?	Yes[4]

Note: [1]This is not explicitly given but is taken as the ambient condition stated by the authors. [2]Values of viscosity and density are taken as those for water under standard conditions. [3]The cost of electricity is not given. Therefore, this was acquired using IEA data for Turkey via DECC [30]. The gas cost data is therefore taken from the same source for consistency purposes. [4]This data was not given explicitly as heat pumps/ORCs are not considered by the authors. However, the KBS results showed that an ORC was viable (see Table 11), therefore this data is inferred from the fact that various hazardous chemicals are used during textile manufacture (during bleaching, for example). Hence, it is assumed toxic and flammable chemicals can be tolerated.

The results generated by the KBS are shown below in Tables 11-13. Table 11shows the initial selection process for which categories of waste heat recovery equipment are available for use. Table 12 shows which liquid-liquid heat exchangers are suitable for the duty. Table 13 shows a comparison of the design results for the available options.

Table 11. WHR equipment available for use in the case study

		Reason
Heat Exchanger Heat Recovery Possible	Yes	N/A
Closed-Cycle Vapour Compression Heat Pump Possible	No	Heat sink does not require a temperature lift in source
Mechanical Vapour Recompression Possible	No	Not an evaporative process
Organic Rankine Cycle Possible	Yes	N/A

Table 12. Heat exchangers available for use in the case study

Heat Exchanger Type	Selection	Reason
Gas-gas heat exchangers	No	Neither heat sink nor source are in the gas phase
Gas-liquid heat exchangers	No	Neither heat sink nor source are in the gas phase
Plate and Frame	Yes	N/A
Brazed Plate	No	Access for cleaning/maintenance not possible with this unit
Welded Plate	No	Access for cleaning/maintenance not possible with this unit
Plate and Shell	No	Access for cleaning/maintenance not possible with this unit
Shell and Tube	Yes	N/A
Spiral	No	Only considered when at least one fluid is a slurry

Table 13. Design results for all available options in the case study

	Shell and Tube Heat Exchanger	Plate Heat Exchanger	ORC
Duty of waste heat recovered (kW)	1854	2029	868
Heat source outlet temperature (°C)	30.0	25.0	58.2
Heat sink outlet temperature (°C)	56.5	60.0	N/A
Heat exchanger effectiveness	84.8	92.1	N/A
Thermal efficiency	N/A	N/A	4.82
Gas saving (kWh/year)	13.3×10^6	14.6×10^6	N/A
Net Power output (kW)	N/A	N/A	41.9
Net units of electricity generated (kWh/year)	N/A	N/A	
Estimate capital cost (£GBP)	12204	5308	108260
Estimate maintenance cost (£GBP/year)	Not given	Not given	2165

Estimate cost savings (GBP/year)	293708	321416	23839
Estimate payback period (years)	0.04	0.02	4.99
Estimate greenhouse gas reductions (tCO_2eq/year)	2451	2682	158
Rank capital cost	2	1	3
Rank payback period	2	1	3
Rank greenhouse gas reductions	2	1	3

The results show that three technologies are superficially viable for use in the case study and selected for preliminary design: shell and tube heat exchanger, plate heat exchanger and organic Rankine cycle. The design results show that both of the heat exchanger options are considerably more favourable than the organic Rankine cycle. This result is as expected, as generally one would not consider use of the organic Rankine cycle for WHR from a single-phase heat source at this temperature. However, the results are included in order to ensure non-bias operation from the system, and to help educate the user of the benefits/drawbacks of ORC waste heat recovery (and other technologies, when applicable).

The results show that the plate-heat exchanger marginally outperforms the shell-and-tube, which again would be expected due to the higher *typical* effectiveness achieved by this unit. As a result, the amount of waste heat recovered is higher, and thereby increasing the values of utility savings and the associate cost/emission savings. The capital cost is also calculated to be lower, which again is common of plate heat exchangers compared to shell and tube due to ease of manufacture.

In the paper by Pulat *et al*, only a shell-and-tube heat exchanger was considered for recovery of the waste heat. The results are shown in Table 14.

Table 14. Results by Pulat *et al* and comparison with knowledge-based system results

		Comment
Heat Source Outlet Temperature (°C)	25.0	5°C lower than KBS result
Heat Sink Outlet Temperature (°C)	60.0	3.5°C higher than KBS result
Heat Exchanger Duty (kW)	2030	1854
Heat Exchanger Effectiveness (%)	92.1	84.8
Estimate capital cost (£GBP)	68803 (full installation) 34400 (HEx only)	12204

Estimate maintenance cost (£GBP/year)	2981	Not given
Estimate cost savings (GBP/year)	263253	293708
Estimate payback period (years)	0.29 (full installation cost) 0.13 (HEx only cost)	0.04
Estimate greenhouse gas reductions (tCO_2eq/year)	Not given	2451

The KBS results show a reasonable agreement with those of Pulat *et* al. There is a slight discrepancy in the effectiveness, duty and therefore the outlet temperatures. This is due to the KBS considering the maximum shell-and-tube heat exchanger effectiveness to be 85% rather than the 92.1% in the design by Pulat *et* al.

The main discrepancy exists in the economic assessment. The cost of the heat exchanger only is roughly three times greater in the work by Pulat *et al* than the KBS estimate. This can be attributed to larger heat transfer area required by Pulat *et* al due to higher duty (10% greater) and lower log mean temperature difference (31% smaller), geographical differences and general inaccuracies in the cost factor method which is used in both cases. Furthermore, the work by Pulat *et* al presents a *final* design and analysis, whilst the KBS results are only preliminary. Hence, it would be expected that a preliminary design would be less accurate than a final design.

Overall, the results show that the system has initially selected the initial *possible* technologies for waste-heat recovery without bias. The results of preliminary design then allow a clear ranking of these technologies according to key results such as capital cost, payback period and emission reductions. The results also show a reasonable agreement with the published case study by Pulat *et al*.

4. Conclusions

Low-grade waste heat recovery presents an opportunity for significant gains to be made in the UK process industries with regards to reducing greenhouse gas emissions and plant utility costs. Several options are available for waste heat recovery, including heat exchangers, heat pumps and organic Rankine cycles which each have merits depending on the needs of the plant in question.

A knowledge-based system has been developed to provide non-bias selection of the most appropriate equipment for waste heat recovery. This is done in two steps. Firstly, the technological limitations of the equipment in the data-base are analysed in order to create a list of possible solutions. Secondly, a preliminary design is performed allowing the options to be ranked according to a user-defined criteria.

Case study testing shows that the system generates useful results, allowing a comparison between various options. The final ranking of equipment highlights the most appropriate technology according to the needs of the plant in question. The data generated by the KBS also shows a reasonable agreement with published results.

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