Extending building simulation software to include the organic Rankine cycle for factory waste heat recovery

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Keywords

waste heat, organic Rankine cycle (ORC), software, simulation, manufacturing

Abstract

Generators based on the organic Rankine cycle (ORC) are used in some industries to generate electricity from waste heat. The supply of heat is rarely constant since it is linked to the operation of processes whose energy use is determined by the manufacturing schedule. The performance of the ORC depends on many factors including the working fluid, the choice of condenser type and whether or not to use a recuperator. The performance of the condenser is influenced by the climate and therefore the location of the factory.

This paper describes an extension of the functions of a commercial building energy modelling software IES to include ORC simulation. Some of the features of IES such as the modelling of energy profiles, the ability to input weather data and the modelling of typical energy system components make it well suited to this task.

The model of a typical ORC system includes the evaporator heat exchanger with its thermal oil pump, the condenser with its pumps and fans and the option of a recuperator, as well as the ORC device itself. As well as selecting the configuration of the ORC system, the software user is able to choose from a wide range of working fluids. The auxiliary energy used by the pumps and fans is modelled since this can significantly offset the electricity generated by the ORC and therefore impact the cost benefits. The user may select an air-cooled or water-cooled condenser, and the psychrometric behaviour of the cooling tower is modelled so that the impact of location on annual performance can be analysed. The use of the software is illustrated by its application to the waste heat from an iron foundry, which is typical of industries with significant waste heat.

Introduction

In 2014, industry accounted for 26 % of energy use within the EU 28 (Eurostat, 2016). In the energy intensive industries, much of the energy used is process related and is driven by the chemical transformations needed to refine raw materials into commodities such as cement, steel and chemicals. However a large number of European industrial activities take place in buildings in which the energy is also used for building services such as heating, lighting and ventilation as well as to drive manufacturing processes. In these industries, energy efficiency analysts may use modelling software to derive estimates of energy used in industrial processes as well as the factory building. Over the years, software tools for industrial process modelling and building simulation have developed as two separate types of application. The former tend to be continuous models of the physical and chemical transformations that take place at the heart of a process, whereas the latter tend to be models of the energy transformations and heat transfer between different building elements and their building services. While both approaches have their place and can be valuable, there is a significant lack of integration between these tools (Wright et al. 2013). This is unfortunate for at least three reasons. First, factory buildings can be used to capture energy (for example using solar photovoltaic panels) but to analyse the cost benefits, one must model the temporal variability of both the renewable energy supply and the demand, which is driven by manufacturing schedule (Khattak et al, 2016). Second, many factories operate energy using devices such as boilers and chillers to provide building services as well as process heat and coolth. The selection of such equipment is influenced not only by the energy requirements of the factory's manufacturing processes but also by the requirements of the building, which are in turn influenced by the local climate. A full analysis therefore requires an understanding of the seasonal influences on building energy, the local climate and thermal efficiency, as well as the manufacturing schedule since there may be significant thermal interaction between industrial processes and factory buildings (Despeisse et al. 2013; Gourlis and Kovacic, 2016). Third, there may be opportunities for capturing waste heat from industrial processes and re-using this in other processes or in the factory building.

Where computer modelling has been applied to improve the operation of manufacturing systems it has traditionally been done using discrete event simulation (DES) in which the behaviour of queues and processes is modelled by a probabilistic analysis of events such as machine breakdown and order arrival. In this way the performance of a manufacturing system in terms of work in progress, cycle time and schedule adherence (for example) can be derived. DES has been applied to industrial energy analysis, but almost always in a way that excludes an explicit analysis of building energy (Mardan and Klahr, 2012; Kohl et al, 2014; Langer et al, 2014).

The importance of modelling process energy and building energy in a holistic manner has been noted by researchers (Hermann and Thiede, 2009; Khattak et al, 2014) and where this has been reported by researchers it is general achieved by modelling both the building and manufacturing processes in a continuous manner (i.e. not as discrete events). An example of such a holistic analysis is described by Hafner et al (2014) and this was also the approach taken during the development of a specialised factory energy modelling tool during the THERM project, with which two of the authors were involved. The THERM software was developed as an extension to an existing building simulation software called IES-VE (Integrated Environmental Solutions Virtual Environment), and it was intended to represent continuous flows of materials, energy and water as well as the interaction of these with the building and its services. THERM allows an analyst to model the factory building geometry and its thermal characteristics as well as those of the key energy using processes within. Within THERM relevant flows of energy carriers such as electricity, water, compressed air, gas and steam are represented, as well as the energy transformations that take place within the factory. THERM models can be driven by real data measured in the factory and they can be used to derive and compare different 'tactics' for reducing energy and material waste (Despeisse et al. 2013). Since it was based on a building energy modelling tool, THERM can be used to model the performance of building mounted energy technologies such as solar panels, but it did not include one particular technology that is becoming increasingly important in industrial energy efficiency – the organic Rankine cycle (ORC). This paper describes the addition of this feature to THERM.

The organic Rankine cycle (ORC)

All industrial processes involve a loss of useful energy, usually in the form of heat, but some processes create waste heat in a form that can be usefully recovered. Industrial waste heat can be used for a range of purposes such as to supply heat to another process (using a heat exchanger or a heat pump in order to deliver heat at the required temperature), to drive an absorption chiller or to supply space heating to a factory building. An increasingly common use of waste heat below 400 °C is to generate electricity using a machine based on the organic Rankine cycle, which represents a flexible and relatively efficient means of generating a benefit from waste heat (Forni et al. 2014; Suomalainen and Hyytia, 2014; Velez et al. 2012).

Organic Rankine cycle devices operate in a similar manner to turbines based on the familiar steam Rankine cycle, except that instead of water, an ORC device uses one of a wide range of organic chemicals as the working fluid. The choice of working fluid is influenced by many factors including toxicity, environmental impact in case of accidental release, stability, cost and thermodynamic properties over the range of temperatures and pressures experienced in the application. For some fluids, the temperature at which heat is input to the evaporation part of the cycle may be as low as 73.3 °C (Auld et al. 2013) while for others it may be as high as 340 °C (Fernandez et al. 2012). Suitable working fluids for ORC include linear, branched and aromatic hydrocarbons, fluorinated hydrocarbons, siloxanes, ethers and alcohols. The range of ORC working fluids available is so wide that there have been many studies into their selection methods and the corresponding choice of expander type such as radial inflow turbine, scroll expander and screw expander. Such studies cover pure fluids as well as mixtures, the latter having the advantage that heat can be supplied and rejected over a wider range of temperatures while working pressure remains constant. Researchers also report ORC performance according to different criteria including first law efficiency, second law efficiency, work output, and exergy efficiency (Bao and Zhao, 2013). Selection of a suitable working fluid is usually carried out by modelling the thermodynamic cycle of the ORC and its ancillary equipment, then running the model under different conditions and with different working fluids whose properties have been tabulated. One such study concludes with the general guidelines that to maximise net ORC power output, a working fluid should be chosen with a critical temperature 30–50 K above the hot source temperature for pure fluids; and 30–50 K below the hot source temperature for mixtures (Haervig et al, 2016).

The wide range of suitable working temperatures means that ORC power systems can be used to generate electricity from a wide range of heat sources and with varying temperatures, including diesel exhaust systems, cement kilns, steel furnaces (Hjartarson et al. 2010), biomass combustion, solar thermal collectors and geothermal boreholes (Velez et al. 2012).

In industrial systems, one of the reasons for a wide variation in hot source temperature is the cyclic nature of many industrial processes in which material is loaded into a vessel before heating, cooling and unloading ready for the next cycle. Under such conditions the temperature of waste process heat will inevitably vary significantly, and the actual performance might be expected to differ significantly from predicted performance based on a simulation study. However by controlling the varia-

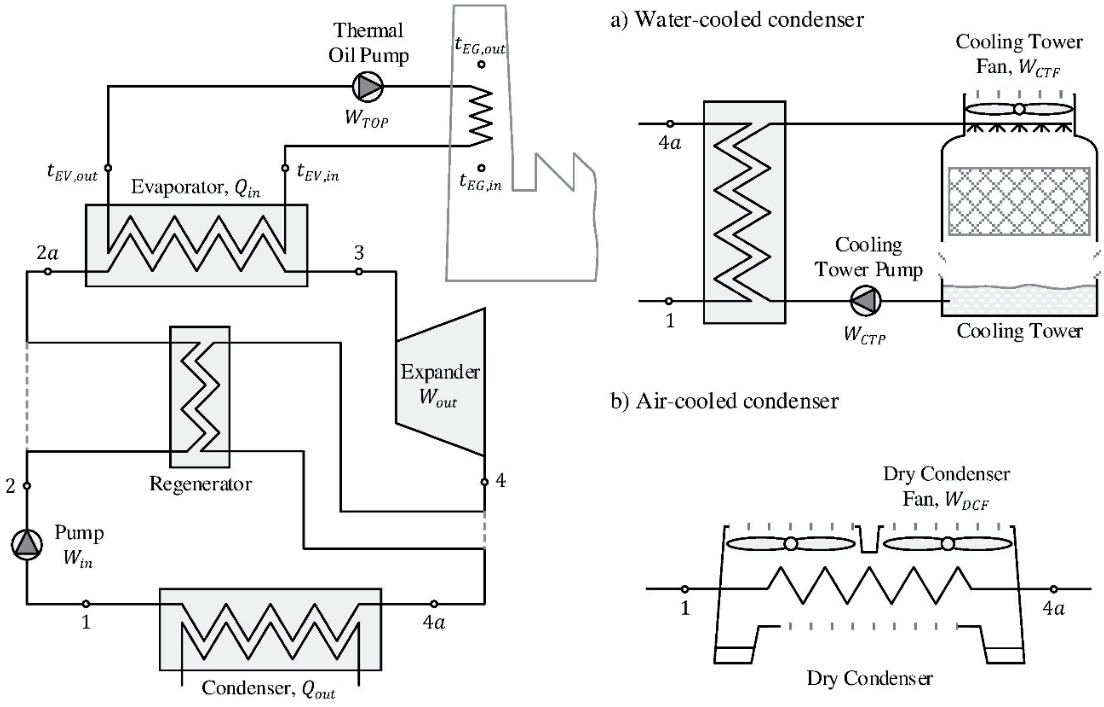


Figure 1. Main components of a power system based on the organic Rankine cycle.

tions of a real process (apart from ambient temperature which cannot be controlled) and making careful measurements it has been shown that a model of an ORC supplied by waste industrial process heat can be validated.

ORC principles

The basic ORC consists of a pump, evaporator, expander and condenser. Many systems also feature a regenerator (sometimes known as an internal heat exchanger) that extracts heat from fluid leaving the expander and uses this to preheat the fluid entering the evaporator (Figure 1).

In the idealised cycle, fluid at state 1 enters the pump where its pressure is increased to the maximum pressure of the cycle before it is heated in an isobaric process, firstly by the regenerator (if present) and then by the evaporator until it reaches the maximum temperature of the cycle at which point it may be superheated. It is then expanded in an expander where the work extracted is used to generate electricity, after which it is cooled firstly in the regenerator (if present) then the condenser, where it is cooled isobarically until it reaches state 1 again. The regenerator is often necessary because for many organic working fluids the temperature of the fluid leaving the expander is significantly higher than that at which it enters the pump (Lai et al. 2011). The ORC may be represented thermodynamically on a temperature entropy diagram as shown in Figure 2.

As well as the choice of working fluid and the temperatures of the heat source and sink, the performance of an ORC is influenced significantly by the presence and design of the internal heat exchanger, and the design of the external heat exchangers used by the evaporator and condenser. In practical applications, the temperature of the heat source may vary and heat may be available only intermittently, for example waste heat from a batch process (Suomalainen and Hyytia, 2014).

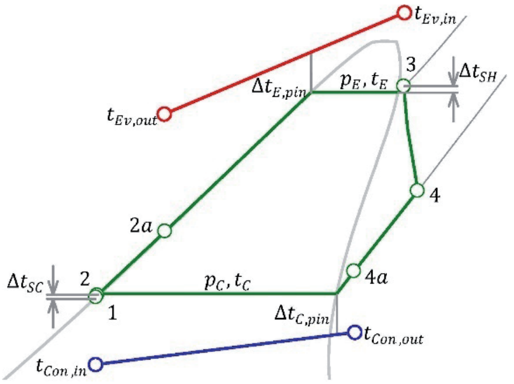


Figure 2. T-s diagram for the organic Rankine cycle.

Unlike the steam Rankine cycle, the evaporator of an ORC may need to be heated indirectly via a thermal oil loop, for example when the heat source is at too high temperature for a flammable working fluid (Lai et al, 2011). Similarly, the heat is rejected from an ORC via a condenser that must be cooled either by water (using a cooling tower) or by air (using a dry condenser) as shown in Figure 1. The heat from the condenser can also be usefully deployed, for example for district heating or absorption chilling (Fernandez et al. 2011).

A full analysis of ORC system performance should therefore consider the performance of the heat exchangers used in the evaporator, condenser and regenerator as well as any auxiliary power used for pumps and fans, etc. The performance of the condenser itself depends upon the climatic conditions in which it operates, including outdoor air wet-bulb temperature (for a cooling tower) and outdoor air dry-bulb temperature for a dry condenser.

Modelling of integrated energy technologies and buildings

This paper describes the extension of the building simulation tool IES-VE to include the modelling of advanced energy technologies such as concentrated solar collectors and generators featuring the organic Rankine cycle. This development continued work that had been initiated during the THERM project mentioned earlier and is supported by the European Union as part of an FP7 research project called REEMAIN (Resource and Energy Efficient Manufacturing – www.reemain.eu). The ORC system under investigation was intended to extract heat from the flue gases of a gas-fired cupola furnace operated by an Italian iron foundry that is one of the REEMAIN partners.

WORKFLOW OF FACTORY ENERGY MODELLING WITHIN REEMAIN

As with THERM, the modelling starts with the definition of the factory geometry and the energy using processes (modelled as 'process components') within the factory. To carry out a simulation study, an IES-VE model of the factory must be created. This requires the collection of site data for both the building and manufacturing operations. Such data consists of drawing of the site (plans and elevations), building construction details (e.g. materials used, thickness of insulation), details of the heating, ventilation and cooling (HVAC) system, process settings and schedules, material flow rates, etc. As with any simulation study, the detail and complexity needed within the model depends on the purpose and scope of the study.

To the model of the factory and the process components are added 'service components' that represent the primary energy using systems within the factory. These convert energy from primary sources to other forms of energy such as steam, hot/cold water, compressed air, etc. The entire workflow is shown in Figure 3.

Following the factory and process modelling, the tool allows the import of both metered data and estimated data that together represent a holistic view of the factory's energy use. Unlike most modern commercial buildings a typical factory has a range of different types of energy meter as well as many energy-using devices for which the consumption is not metered and therefore needs to be estimated somehow. These problems are addressed in a novel way within the software, which contains powerful features to process metered data so that it can be 'cleaned up' for use by the software, for example extrapolating where necessary and highlighting suspect data for editing or deletion by the user.

Metered data are collected automatically or manually using a web-based tool called SCAN which then represents the energy data as 'freeform profiles' (FFD). SCAN also contains a method for estimating energy data using a variety of techniques including questionnaires, interviews with experienced staff, use of standardised profiles and analysis of utility bills.

Specific energy technologies such as PV, solar thermal panels and solar concentrators are modelled using software based on the existing Apache HVAC tool within IES, or other languages as appropriate including Python (2016) which was used to model the ORC. These technology simulators are accessed within the IES software in the form of decision support tools (DST). At present, these tools are not run at the same time as

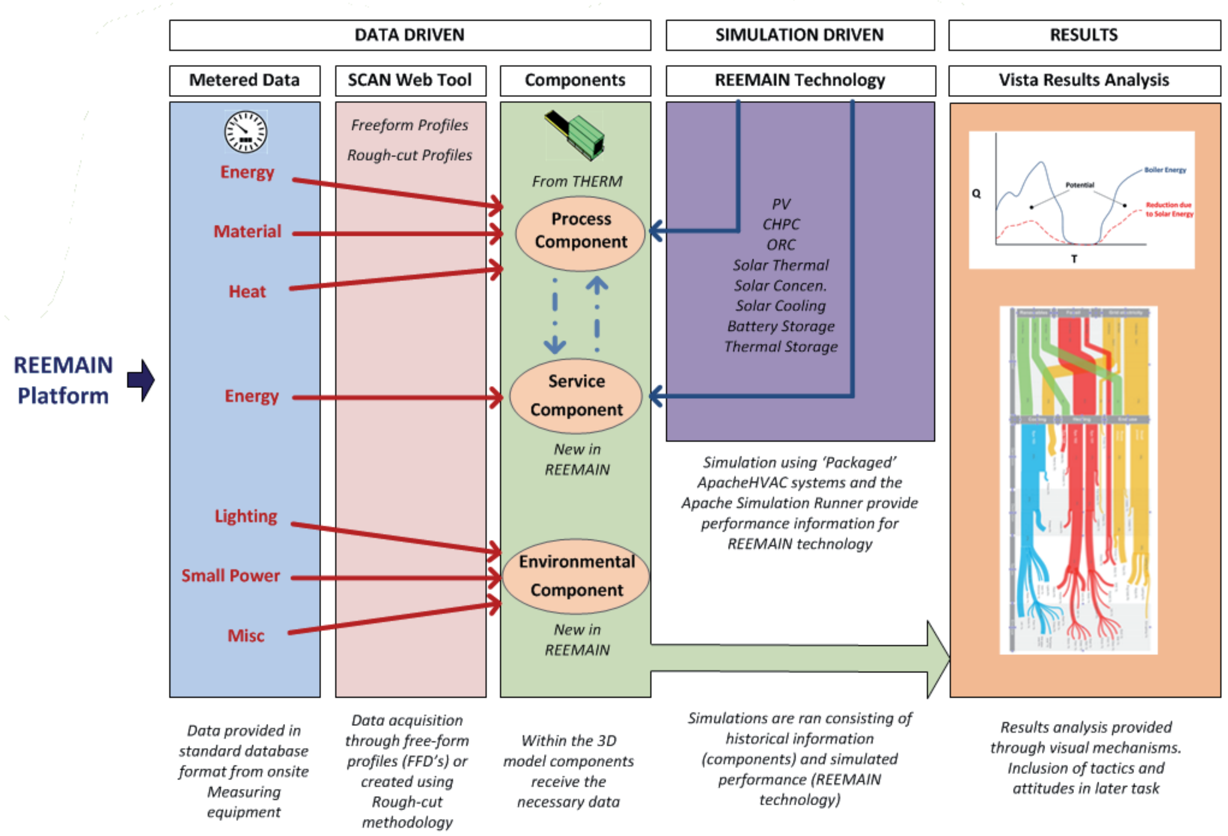


Figure 3. Workflow for the REEMAIN factory energy modelling platform.

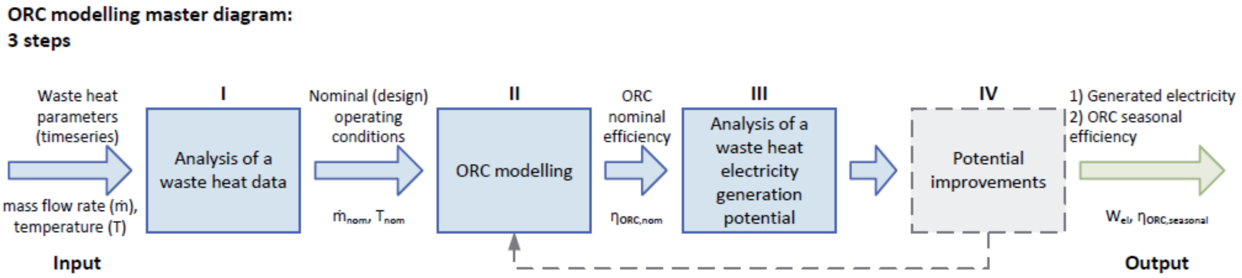


Figure 4. ORC engine – master modelling diagram.

the building modelling software, instead they are run as the second stage of a two stage process following a simulation run of the main software. In this sense the energy modelling technologies are not fully integrated within the main software, but are used instead to evaluate the operation of specific energy technologies on

Modelling the ORC as a component of an energy system

In order to model the performance of an ORC in a system for the recovery of industrial waste heat, one must model the operation of heat exchangers as they respond to variations in both input energy and heat rejection. The former is driven by industrial process variability while the latter is driven by the climate. Climate modelling is a strong feature of building modelling tools like IES and the ORC modelling feature makes full use of weather file data to take account of location specific variations in humidity and temperature.

The approach taken to the modelling process was firstly to develop a Python model (www.python.org/about) of a specific ORC energy system that had been proposed for use by one of the REEMAIN partners. Korolija and Greenough (2016) provide a full description of the modelling approach.

Although it was not possible to validate this model of an ORC system, the authors were given access to temperature and mass flow data for the cupola flue gases, which were used to size the ORC for modelling purposes and derive the heat input parameters. Once the model had been prototyped in this way, it was passed to the software engineers at IES to be developed into a feature within their product. While the prototype model represented a particular ORC energy system intended for use with a particular heat source, the IES code was developed in such a way that users will be able configure their ORC models by selecting suitable design and operational parameters according to the intended operating context.

The development of the ORC modelling functionality within the IES-VE software took place in two phases, the ORC engine and the graphical user interface (GUI). The ORC engine was written in the open source programming language Python 3.0 (Python, 2016), while the GUI was written within the Python coding environment of the VE using Python's de-facto standard GUI package TkInter (https://wiki.python.org/moin/TkInter). The integration of the ORC engine and GUI takes place within the IES-VE software.

All working fluids available for selection by the user are 'dry fluids' whose thermophysical properties were obtained from CoolProp, an open-source thermophysical property library (Bell et al. 2014). The selection of the fluids is based upon the work of Korolija and Greenough (2016).

A master modelling diagram of the ORC engine is shown in Figure 4. Key input parameters are discussed in the following section. Step 1 is a simulation run of the building modelling software, which generates a results file that is accessed by the decision support tool (DST) being used, in this case the one for the ORC.

Figure 5 is a screenshot of the ORC modelling software, showing the design of the GUI. The tabs labelled *Sankey*, *Automation* and *Manual*, as well as the pull-down menus labelled *Select attitude:* and *Select tactic* allow the user to configure the model of the ORC within the framework of the decision support tool.

SETTING THE MODELLING PARAMETERS

The inputs to the ORC model are process data and other data supplied from the VE. These data can be simulated data, metered data or a combination. The following workflow is used to model a factory and examine the operation of an ORC according to specific parameters that are input via the DST user interface:

- The user creates a model of the factory using IES-VE, and runs a simulation to create a results file.
- The user launches the ORC tool from the decision support tool within IES-VE.
- The user selects the results file, the period of analysis and the analysis 'theme' (i.e. energy).
- The appropriate 'attitude' and 'tactic' are selected (in this case, the attitude is *Change*, and the tactic is *Add Renewable – ORC*).
- The decision support tool 'focus' controls are used to select the process in question and its variables (in this case, mass flow rate and temperature). Time series data are passed to the ORC modelling engine.
- The appropriate weather location is selected from a drop-down menu. Time series dry bulb and wet bulb temperatures are passed to the ORC engine so that it can take into account the weather conditions since these affect the performance of the ORC condenser.
- Details of the ORC engine are selected from drop-down menus and passed to the ORC engine:

  - Type (i.e. air-cooled or water-cooled condenser).
  - Refrigerant (a limited selection is currently available, comprising Isopentane, R245fa, 1-Butene and n-Pentane).
  - Heat recovery (i.e. whether a recuperator is used – Yes or No).
  - Condensation pressure limit (may be set to reduce the risk of any non-condensable gas from the outside environment penetrating the system due to reduced pressure – 1.1 atm or No).
- The user selects 'run test' and the ORC engine is engaged and runs a simulation.
- Results are displayed within the message window of the decision support tool to indicate ORC performance to the user (Figure 5).
- The following results are presented to the user:
  - Warning messages (errors).
  - Waste heat used by the ORC (Wh), ORC generated electricity (Wh), thermal oil pump electricity consumption (Wh) and System seasonal coefficient of performance (COP)).
  - For systems with a water-cooled condenser; cooling tower pump electricity consumption (Wh) and cooling tower fan electricity consumption (Wh) are presented.
  - For systems with an air-cooled condenser; dry cooler fan electricity consumption (Wh) is presented.

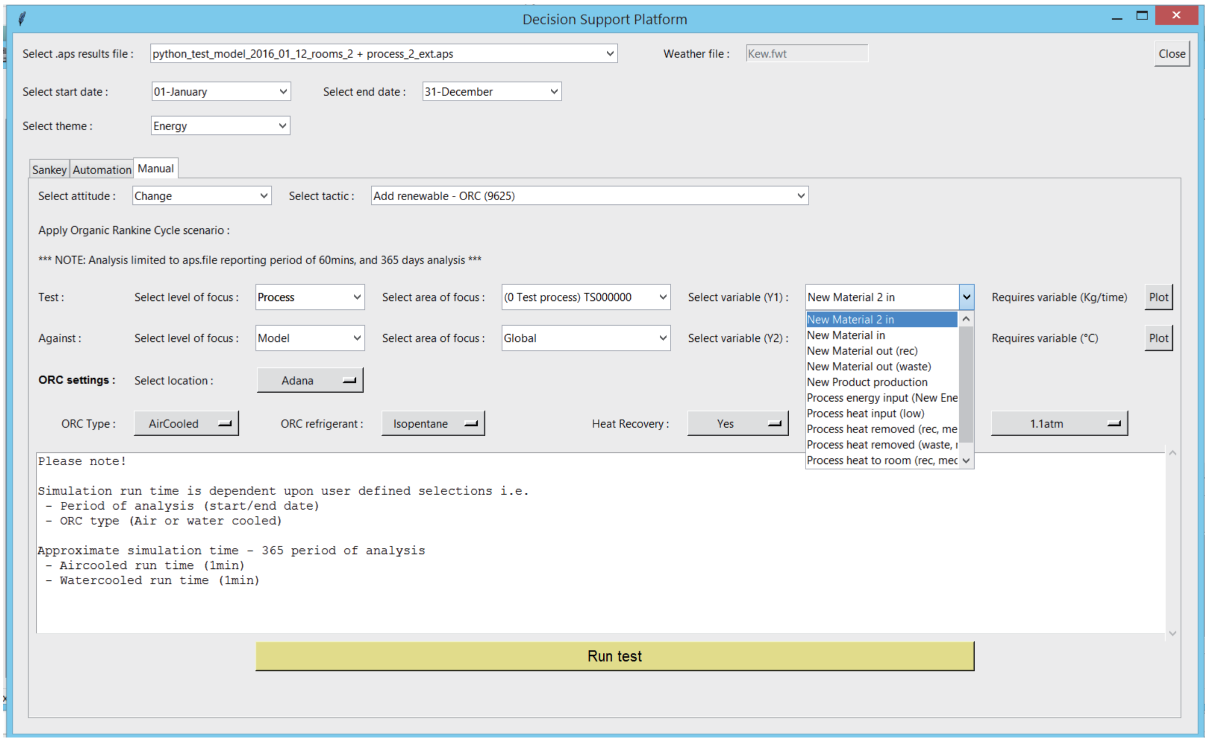
Use case

The ORC model has been applied to a demonstration case study from the REEMAIN project. The demonstration site is a foundry based in Italy. Following the steps of the ORC workflow as discussed above, a model was created within the IES-VE software, which includes building and process geometry and associated data. This model is shown in Figure 6.

Metered data was obtained from the Supervisory Control and Data Acquisition (SCADA) system used by the foundry. Specific data captured for this study relate to the temperature and mass flow rate of the exhaust gas. These data were input to the IES-VE software that converted them to a 'freeform profile' that was then attached to the cupola furnace process within the model. After finalising the data inputs the simulation was run. This generated a results file. The decision support platform containing the ORC modelling tool was then launched from within the IES-VE. Figure 7 shows some of the model parameters used within this use case.

A standard IWEC format (international weather for energy calculations) file called VeniceIWEC.fwt was used to represent the climate, which contains dry bulb and wet bulb temperature for the modelled period. This file represents the closest weather location currently available within the IES-VE software. In future a weather file will be used that more accurately represents the climate within the vicinity of the demonstration site. Metered data obtained from the site was only available from 1st January until 31st August 2015, so it was not possible to model operations over an entire year.

Exhaust temperature and mass flow rate data associated with the cupola furnace during the modelled period are shown in Figure 8 and Figure 9 respectively.



Select .aps results file : python_test_model_2016_01_12_rooms_2 + process_2_ext.aps
Weather file : Kew.fwt
Select start date : 01-January
Select end date : 31-December
Select theme : Energy
Select attitude : Change
Select tactic : Add renewable - ORC (9625)

Apply Organic Rankine Cycle scenario :

*** NOTE: Analysis limited to aps.file reporting period of 60mins, and 365 days analysis ***

Test : Select level of focus : Process
Select area of focus : (0 Test process) TS000000
Select variable (Y1) : New Material 2 in
Requires variable (Kg/time)

Against : Select level of focus : Model
Select area of focus : Global
Select variable (Y2) :
Requires variable (°C)

ORC settings : Select location : Adana

ORC Type : AirCooled
ORC refrigerant : Isopentane
Heat Recovery : Yes
1.1atm

```
Please note!

Simulation run time is dependent upon user defined selections i.e.
 - Period of analysis (start/end date)
 - ORC type (Air or water cooled)

Approximate simulation time - 365 period of analysis
 - Aircooled run time (1min)
 - Watercooled run time (1min)
```

Figure 5. Screenshot of the ORC modelling tool developed for the IES-VE, showing the GUI.

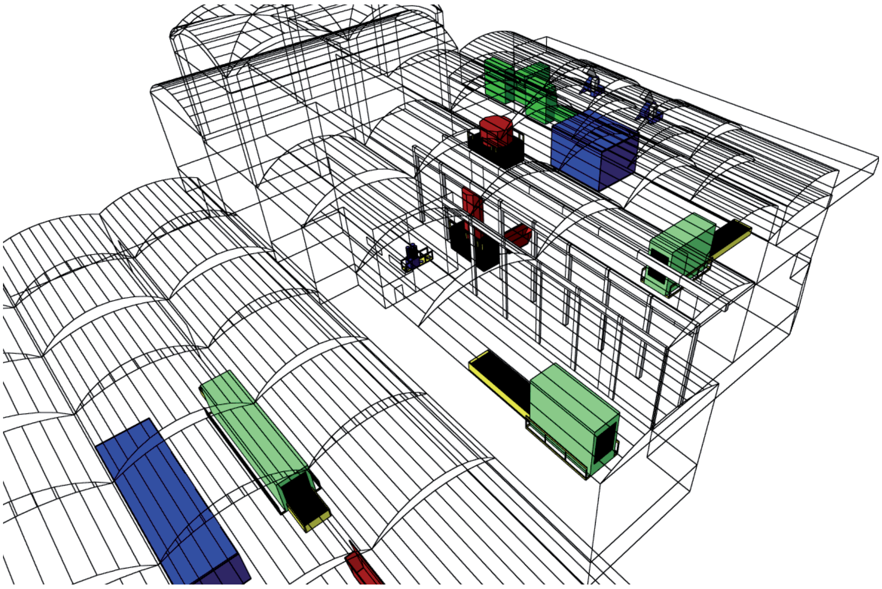
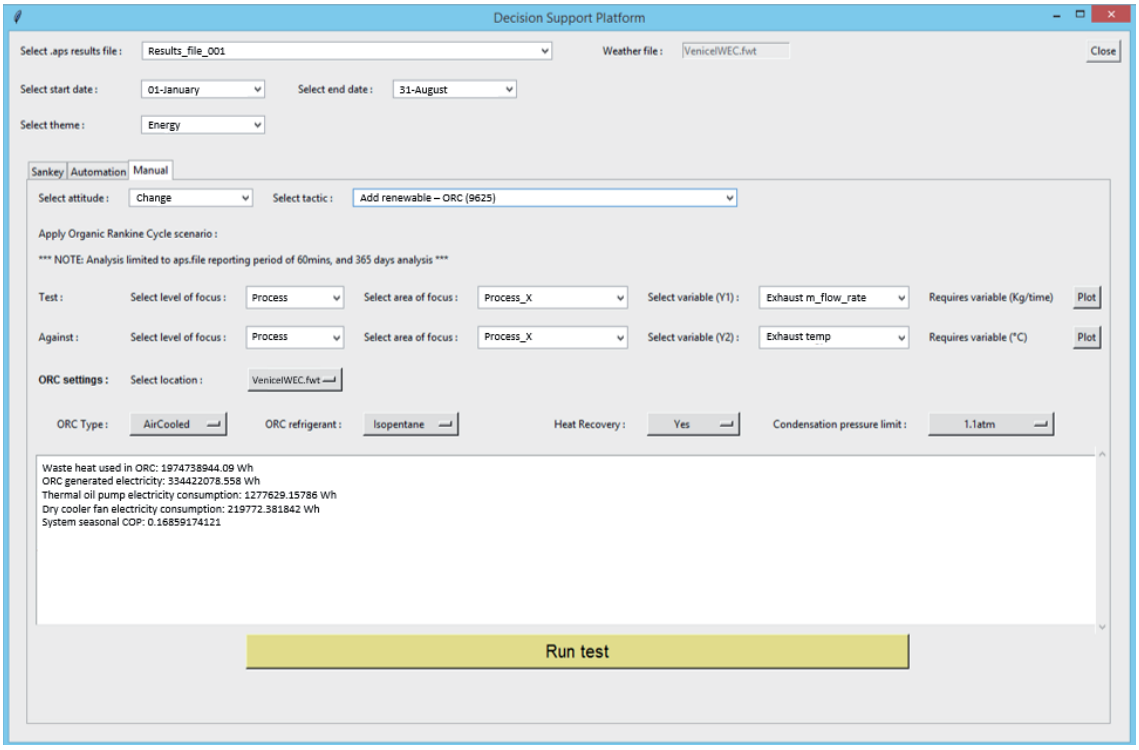


Figure 6. Building and process geometry modelled for the foundry use case.



Select .aps results file : Results_file_001

Weather file : VeniceIWEC.fwt

Select start date : 01-January

Select end date : 31-August

Select theme : Energy

Select attitude : Change

Select tactic : Add renewable – ORC (9625)

Apply Organic Rankine Cycle scenario :

*** NOTE: Analysis limited to aps.file reporting period of 60mins, and 365 days analysis ***

Test : Select level of focus : Process Select area of focus : Process_X Select variable (Y1) : Exhaust m_flow_rate Requires variable (Kg/time)

Against : Select level of focus : Process Select area of focus : Process_X Select variable (Y2) : Exhaust temp Requires variable (°C)

ORC settings : Select location : VeniceIWEC.fwt

ORC Type : AirCooled ORC refrigerant : Isopentane Heat Recovery : Yes Condensation pressure limit : 1.1atm

```
Waste heat used in ORC: 1974738944.09 Wh
ORC generated electricity: 334422078.558 Wh
Thermal oil pump electricity consumption: 1277629.15786 Wh
Dry cooler fan electricity consumption: 219772.381842 Wh
System seasonal COP: 0.16859174121
```

Figure 7. ORC model input parameters.

EXPERIMENTAL DESIGN

The high variability of both waste heat temperature and exhaust gas mass flow rate complicates the selection of nominal ORC capacity. At present, the ORC capacity is not configurable and the software has been written to assume an ORC capacity that matches the 90th percentile of all temperatures recorded and the 90th percentile of waste exergy. For the time series data shown above, this equates to the following values:

- Nominal heat source temperature: 459.84 °C
- Nominal heat source mass flow rate: 7.82 kg/s

Korolija and Greenough (2016) claim that the climate can have a significant effect on the efficiency of an ORC for a given source of waste heat, because differences in wet bulb temperature and dry bulb temperature affect the operation of the condenser. For this reason, the ORC analysis tool within IES-VE was tested using two sets of simulation runs; one set featuring an ORC with an air-cooled condenser and the other set with a water-cooled condenser. For each type of condenser, the simulation was run with four different working fluids, with and without a recuperator, and with and without a limit on condensation pressure.

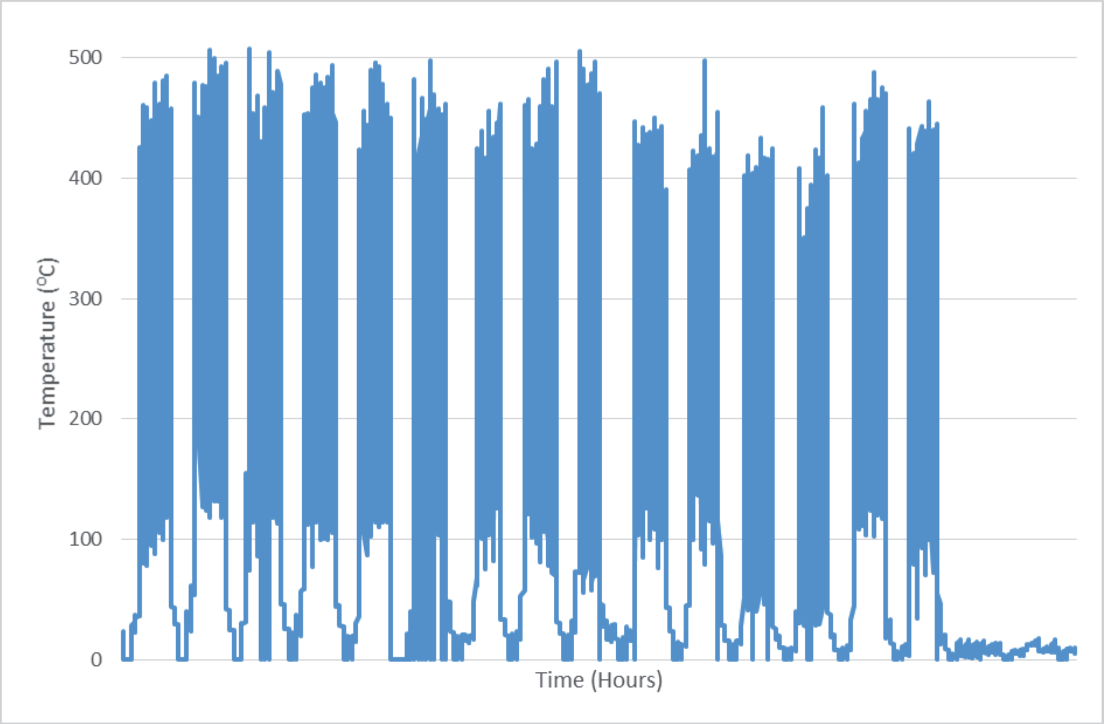


Figure 8. Process exhaust temperature.

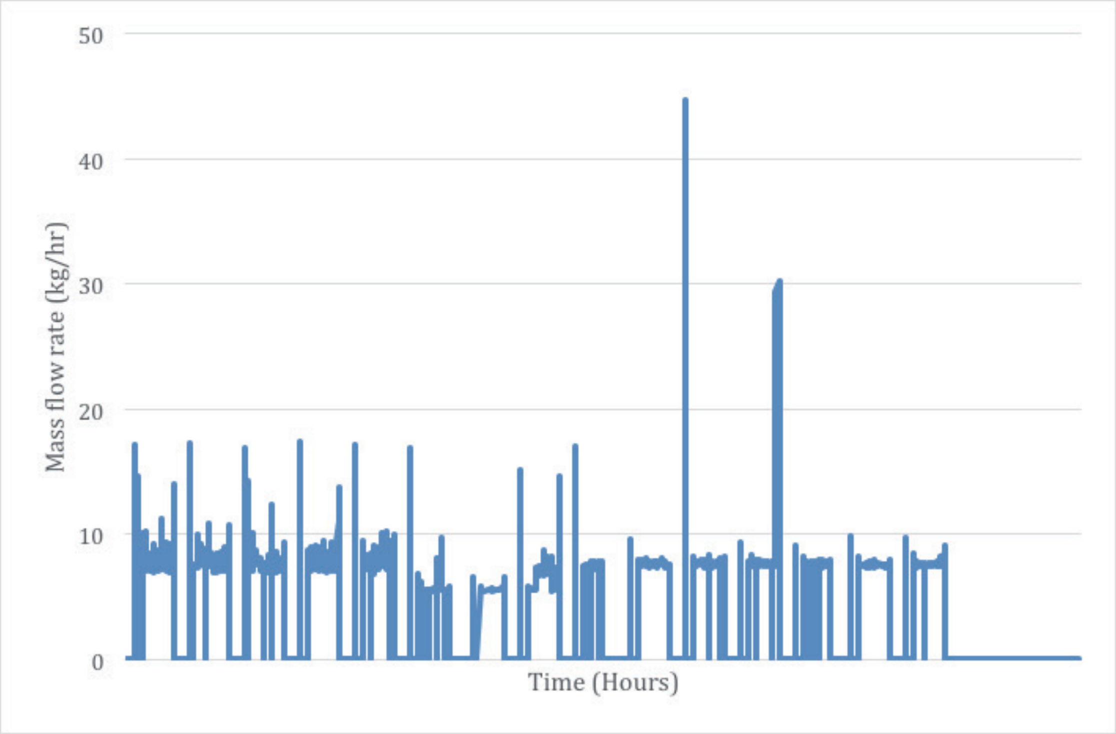


Figure 9. Process mass flow rate.

RESULTS

The different model settings and simulation results for the ORC with an air-cooled condenser and those for an ORC with a water-cooled condenser are shown Table 1 and Table 2 respectively.

Conclusions

The development of a factory energy modelling software tool has been described. This work continued work that was initiated during a UK government sponsored research project called THERM in which a building energy modelling tool was extended to include simulation of specific process technologies in order to facilitate energy analysis and identification of energy saving opportunities. The current project (REEMAIN) extends the THERM software to include the modelling of energy generation technologies including the ORC, the further development of features for the input and 'cleanup' of metered data and the creation of representative energy profiles where required data do not exist. This paper has briefly described the workflow of the new modelling tool, which is believed to be novel in its integration of advanced building simulation with decision support functionality in relation to advanced renewable energy technologies. The integration is not complete and the modelling is currently a two-stage process during which the results generated by stage 1 are used in stage 2 in which the effectiveness of the generation technologies is analysed. For this reason a fully integrated dynamic simulation is not currently possible, although this is intended for future development. The novelty of the tool is that it makes use of the powerful building modelling features of a commercially available building modelling tool and extends these to bring additional analytical power to users of the existing software. The case study described illustrates this by making use of the climate modelling and metered data analysis features of the existing tool to calculate the impact of climate on the performance of an ORC.

Although it has not yet been possible to validate the ORC analysis software, the description of the modelling approach and the results obtained illustrate how this new feature of an established tool can be used to analyse the performance of an ORC in the context of waste industrial heat. In the example given, the integration of an ORC with the exhaust system of a cupola furnace situated near Venice has been analysed. The software allowed the analyst to compare the performance of an ORC used to extract electrical energy from a highly variable heat source characterised by data that had been collected from a real foundry over a period of eight months. The analysis compared ORC systems with air-cooled and water-cooled condensers, with or without a recuperator, using a selection of working fluids and with a condensation pressure limit of 1.1 atm or not. The results show that electricity generation is maximised by using a water cooled condenser, with n-pentane as the working

Table 1. Settings and results for ORC with air-cooled condenser.

	ORC settings				ORC results				
Simulations	ORC Type	ORC Refrigerant	Heat recovery	Condensation pressure limit	Waste heat used in ORC (MWh)	ORC generated electricity (MWh)	Thermal oil pump electricity consumption (MWh)	Dry cooler fan electricity consumption (MWh)	System seasonal COP
Test_001	Air-cooled	Isopentane	Yes	1.1atm	1974.74	334.42	1.28	0.22	0.17
Test_002	Air-cooled	R245fa	Yes	1.1atm	1974.74	257.37	1.28	0.25	0.13
Test_003	Air-cooled	1-Butene	Yes	1.1atm	1974.74	235.25	1.28	0.26	0.12
Test_004	Air-cooled	n-Pentane	Yes	1.1atm	1974.74	352.24	1.28	0.22	0.18
Test_005	Air-cooled	Isopentane	Yes	No	1974.74	334.42	1.28	0.22	0.17
Test_006	Air-cooled	R245fa	Yes	No	1974.74	257.38	1.28	0.25	0.13
Test_007	Air-cooled	1-Butene	Yes	No	1974.74	235.26	1.28	0.26	0.12
Test_008	Air-cooled	n-Pentane	Yes	No	1974.74	352.24	1.28	0.22	0.18
Test_009	Air-cooled	Isopentane	No	1.1atm	1974.74	281.64	1.28	0.14	0.14
Test_010	Air-cooled	R245fa	No	1.1atm	1974.74	238.08	1.28	0.20	0.12
Test_011	Air-cooled	1-Butene	No	1.1atm	1974.74	224.68	1.28	0.23	0.11
Test_012	Air-cooled	n-Pentane	No	1.1atm	1974.74	297.16	1.28	0.14	0.15
Test_013	Air-cooled	Isopentane	No	No	1974.74	281.64	1.28	0.14	0.14
Test_014	Air-cooled	R245fa	No	No	1974.74	238.08	1.28	0.20	0.12
Test_015	Air-cooled	1-Butene	No	No	1974.74	224.69	1.28	0.23	0.11
Test_016	Air-cooled	n-Pentane	No	No	1974.74	297.17	1.28	0.14	0.15

Table 2. Settings and results for ORC with water-cooled condenser.

	ORC settings				ORC results					
Simulations	ORC Type	ORC Refrigerant	Heat recovery	Condensation pressure limit	Waste heat used in ORC (MWh)	ORC generated electricity (MWh)	Thermal oil pump electricity consumption (MWh)	Coolong tower pump electricity consumption (MWh)	Coolong tower fan electricity consumption (MWh)	System seasonal COP
Test_017	Water-cooled	Isopentane	Yes	1.1atm	1975.15	370.56	1.28	21.25	0.57	0.18
Test_018	Water-cooled	R245fa	Yes	1.1atm	1975.15	294.38	1.28	22.29	0.59	0.14
Test_019	Water-cooled	1-Butene	Yes	1.1atm	1975.15	272.74	1.28	22.58	0.60	0.13
Test_020	Water-cooled	n-Pentane	Yes	1.1atm	1975.15	384.41	1.28	21.06	0.56	0.18
Test_021	Water-cooled	Isopentane	Yes	No	1975.15	370.56	1.28	21.25	0.57	0.18
Test_022	Water-cooled	R245fa	Yes	No	1975.15	294.38	1.28	22.29	0.59	0.14
Test_023	Water-cooled	1-Butene	Yes	No	1975.15	272.74	1.28	22.58	0.60	0.13
Test_024	Water-cooled	n-Pentane	Yes	No	1975.15	387.74	1.28	21.02	0.56	0.18
Test_025	Water-cooled	Isopentane	No	1.1atm	1975.15	308.39	1.28	22.10	0.59	0.14
Test_026	Water-cooled	R245fa	No	1.1atm	1975.15	269.22	1.28	22.63	0.60	0.12
Test_027	Water-cooled	1-Butene	No	1.1atm	1975.15	258.39	1.28	22.78	0.61	0.12
Test_028	Water-cooled	n-Pentane	No	1.1atm	1975.15	318.61	1.28	21.96	0.59	0.15
Test_029	Water-cooled	Isopentane	No	No	1975.15	308.38	1.28	22.10	0.59	0.14
Test_030	Water-cooled	R245fa	No	No	1975.15	269.22	1.28	22.63	0.60	0.12
Test_031	Water-cooled	1-Butene	No	No	1975.15	258.38	1.28	22.78	0.61	0.12
Test_032	Water-cooled	n-Pentane	No	No	1975.15	323.75	1.28	21.89	0.58	0.15

fluid, with a recuperator and with no limit on the condensation pressure. The result is not too surprising, however the use of a recuperator and a water cooled condenser both add cost to the ORC system, and the decision not to limit the condensation pressure may risk corrosion of the evaporator heat exchanger if the exhaust gas temperature drops below the acid dew point. An important use of the software is to allow a decision maker to judge whether the additional electricity generation is worth the additional cost and risk of the selected ORC system design.

The ORC model within the IES-VE software is at an early stage of development but its inclusion within an established building simulation tool is expected to appeal to factory designers who wish to consider building energy simulation alongside the conventional rules of design for effective materials flow.

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Acknowledgements

The authors would like to thank the European Commission and the partners in the FP7 project REEMAIN (grant agreement 608977) for funding this research and providing empirical data.