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The use of process integration technology in greenhouse energy systems

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Abstract

This paper introduces the concept of process integration techniques, as developed by others, for application to commercial greenhouse systems. Process integration was originally developed by Linnhoff *et al* (1984) within the chemical process industry and subsequently successfully applied in many other sectors. The technique involves comparing energy streams in a qualitative and quantitative manner to produce a theoretical minimum energy input value with options for assessing various changes to plant functionality for maximum energy savings. This has been extended over the years to permit economic factors to be built in to the whole.

The system developed is designed to be operated as either a stand alone item for an audit purpose, or in the future to be linked to the environmental computer such that an on-going analysis can be maintained showing actual performance against the theoretical minimum.

The software described has been developed as a holistic one, considering all system inputs and outputs. The former are primarily raw energy (gas, electricity etc), but include secondary items such as fertiliser, water and packaging. System outputs are mainly in the form of product, packaging and waste materials. Energy streams are considered to be as one of three types – conventional Temperature Enthalpy (T-H) streams (eg heating), quantitative input streams (eg water), and energy consumption (process) - enthalpy - product quantity streams (eg volumetric output). In addition to these complications there are several external restraints, for example limitations on recycling of water due to pest and disease issues. Some elements, such as thermal buffer tanks, effectively take multiple roles depending on state. The software has been developed using a Object Orientated Programming (OOP) techniques in C++ using MFC for the Windows front end and ChartFX for graphing. Data exchange to environmental computers is at present via Excel sheets, but it is proposed that XML be adopted for this purpose.

The programme outputs are in the form of a the theoretical minimum energy input, the current energy input and the practically achievable one. Suggestions for improvements to energy efficiency are listed and ranked in order of energy saving potential, but with no linking to economic considerations as yet. These are via the output screen, with options for graphical representations in terms of data summaries and reports.

Data from environmental computer systems in commercial blocks for both edibles and ornamentals has been used to undertake initial evaluation of this approach, and results with these test data sets is given.

The need for benchmarking and for objective assessment of energy efficiency has recently been highlighted within the UK by the need for the industry to demonstrate efficiency improvements in order to maintain the Climate Change Levy (CCL) reduction. This currently presents obvious difficulties in comparing year on year data without taking into account meteorological and cropping variations. The approach outlined permits such an objective assessment although is to a certain extent dependent on more subjective data in terms of yield response to different cropping regimes.

1. Description of process integration technology

Process integration is a well known procedure which has been used successfully for several years in ma industries where there are inputs which are both qualitative and quantitative, with the original examp being distillation processes with heating and cooling. Process Integration (Pinch) technology allows t theoretical minimum energy input to be determined and the key heat exchanger to be identified for t process - the "Pinch", and identifies the critical component in the process and the theoretical minimu energy use, allowing objective assessment of energy efficiency and subsequent improvements. T technology has also been successfully applied to water use, considering various qualities of wat cogeneration systems, mass transfer networks, multiple refrigeration plant and even quality assuran protocols. The initial application within multiple distillation columns is the simplest for illustrati purposes. The various heating and cooling processes may be considered in graphical form, with t temperature at start and end of process, and the energy used within it plotted as a series of curv (composite curves), one for heating and one for cooling. The key heat exchanger can then be determin and the affect on total cooling and heating load predicted for any change in delta T of this heat exchanger

2. Application to commercial greenhouses

The system outlined below considers the inputs / outputs in their component values within a softw package that has been developed with output in the form of theoretical minimum energy inputs for particular site as a comparison to actual use, achievable minimum energy inputs and recommendatio The justification for this is multiple: for conventional energy savings due to economic returns, to satis audit protocols, for evidence of true energy reduction for Climate Change Levy exemptions, for objecti rather than subjective comparisons with other growers, and for identification of the most signific processes for improvement. This will then allow the development of a coherent improvement strategy w quantifiable goals and objective comparisons year on year and with other sites.

Inputs can be considered as the primary energy ones, such as gas and electricity, and secondary in terms materials. For example water has an energy value in terms of catchment storage, processing and delive which is reflected in the purchase price, and can also be defined both qualitatively and quantatively. Cr residues also have various values in terms of direct energy (locked carbon) and secondary energy, example that required to produce the nutrients locked in them. Likewise fuel burnt for heating al produces CO_2, of which a proportion is currently used on many sites to aid plant photosynthetic activity.

3. Literature review

Basic studies and descriptions of Process Integration and Pinch Technology are numerous, and reviews ar periodically written by Linnhoff and others, and such foundation material is not considered here. It is interesting to note that as far back as 1991 the potential for applying pinch technology and process integration to "accomplish multiple process improvement objectives" was realised (Rossiter, 1991). The list of possible issues included reduction of wastes and emissions, debottlenecking, reduction of capital an operating costs, and improved operating flexibility. With regard to this project there are several components for which further studies of literature have been undertaken, which are detailed below.

Batch processes.

Most glasshouse processes are time variable, and therefore although a continuous process, they have many time dependent variables which make them fit within the definition of batch processes as opposed to continuous fixed ones. Within the definitions offered by Linnhoff (1993) glasshouse production would be considered as an amalgam of several, having some of the characteristics of both designated and multi purpose production and cyclic and random processes. Of the authors' definition of main parameters only 2 are pertinent to this scenario: heat flow and equipment capacity. Early work by Kemp (1991) describes 3 methods for handling batch processes: Time Average Model, Time Slice Model, and Time Dependent Heat Cascades. Only the latter is likely to be suitable for the processes under consideration here. It is interesting to note that Kemp discounts this procedure on the basis of heat storage costs and recognition that energy costs are minor compared to product yield and quality. Stoltze *et al* (1993) did consider heat storage systems, and included cost benefit analysis, with some options claiming a 28% energy saving, but with optimal savings of 16%.

Cogeneration.
There are some sites with cogeneration plant installed, and there is undoubtedly scope for such plant in energy terms, although current UK economics are having an adverse affect upon new installations and operation of existing ones (cf UK Government consultation over CHP, 2002). Sarabchi & Polley (2002) attempted to consider full integration of the gas turbine cogeneration plant with the whole process, also evaluating individual component streams of the turbine unit. NOx and other emission from gas turbines or scrubbed reciprocating units are low enough for utilisation in glasshouses, and can therefore be considered both in the cogeneration stream and also mass transfer (CO_2) (Marchant *et al*, 2000).

Mass transfer.
Mass Exchange Networks (MENs) are relevant insofar as the CO_2 enrichment of the glasshouse environment is concerned. The parameters that are relevant are the internal and external composition of air, and the CO2 enrichment system (either exhaust gases or pure CO_2). The system proposed by Halwagi *et al* (1989) is difficult to apply to the problem considered here, as the streams are limited both in number and location, and such an approach would be over complicated for minimal results.

Water conservation.
This can be considered alone (e.g. Tripathi, 1996) or in conjunction with energy use (e.g. Cripps, 2000). The latter suggests a first step of considering flow streams and simulation of heat and material balances prior to undertaking pinch analysis. Water consumption and associated energy use can be reduced dramatically in some cases, for example a 60% reduction on raw water use and 65% reduction in effluent discharge was achieved in the Kiwi Dairies plant (Peng *et al*, 2002). Rutkowski *et al* (2001) considered various processes including steam and direct heating, along with cogeneration, at a paper and pulp mill, and also included marginal costs of utilities.

Total site integration.
Linnhoff *et al* (1984) recognised early on in the development of this technology that whole site systems needed to be considered, rather than just single process systems. Total Site profiles are one method of achieving this, linking together many different processes as a thermodynamic representation of the whole. Another element of such an approach is the possibility of considering global site CO2 emissions, (cf Linnhoff *et al* 1993). Axxelson *et al* (1999) considered fuel switching as part of such a CO2 minimisation analysis, a possibility on some glasshouse sites.

Low temperature processes.
Dhole *et al* (1994) considered refrigeration shaft power as a means of considering this system as a part of the wider whole. This is a method for avoiding detailed analysis of the actual refrigeration system itself, and as such can offer a useful tool for approximating energy flows.

Quality assurance.
Some larger companies are now seeing the environmental management audit protocol ISO 14001 as being a valuable standard to achieve, and as part of this have undertaken Pinch technology analysis of operations (Makino *et al*, 2000). This considers water use, wastewater discharges and contaminant levels, volatile organic compounds emissions and waste utilisation. Although this is not a likely scenario for many UK growers, it is one that larger ones may consider, and also links in with Audit Protocols for supermarkets.

4. System methodology
Conventional Stream Tables were developed for main energy items, with separate high, medium and low temperature streams designated. As a part of this process it became clear that the following aspects of Total Site Integration will need to be considered in a special manner within the methodology.

Buffer tanks.
These need to be thought of as a heat exchanger taking with primary water temperature entering at input temperature and leaving at output temperature, and secondary water vice versa, with exchanger efficiency of 100%. This method allows for stream flows to be considered in the normal manner. The time dependent manner and capacity of the system has been included by splitting the unit into two high and low temperature HEN's, with reversal of flow direction considered by means of having two sets of units, available exclusively.

System buffering.
Greenhouse systems sometimes operate on aggregatetemperature rather than specific target temperature, since plants have a good averaging and aggregating ability. This allows the greenhouse total thermal mass to be considered as further buffering.

Linking.
Several component streams need to be considered holistically, i.e. their values are not restricted to one energy activity, for example irrigation water has an energy value due to its production, due to its delivery (pumping) and al so associated with the feed. There is also a mass factor considered in the mass exchange network.

Restraints.
Certain stream s have non-energy linked constraints which will typically effect quality or other production matters, for example irrigation water recycling can also pass on pests and diseases, and recirculation can cause sodium toxicity problems after a period.

Electrical efficiency.
There needs to be a method of considering electrical efficiency of generation. This is relevant when considering on site cogeneration on greenhouse sites where under certain circumstances not only is the heat and power used at ain excess of 90% efficiency but also part / all of the CO_2 is sequestered by the crop. A base level of efficiency for grid supplied electricity has been assumed taking into account generation and distribution efficiencies.

Time variability.
The system needs to be considered along the lines of a Time Dependent Heat Cascade within the definitions discussed previously, and this time dependency has to be extended beyond the controlled processes to consider external time dependent variables, which in holistic energy terms play a key role.

In summary streams will need to be considered under the following categories, principally derived from t ornamentals sector model, since this has the greater number of streams. The edibles sector will effectivel form a subset of this.

T-H defined.
Streams within this are hot water (3), irrigation feed water, boiler flue gases, condenser, CHP exhaust, buffer tanks (2 off), system thermal buffering, conduction / convection / radiation, venting.

Quantitatively defined streams
Streams defined in this way include primary fuel, water, compost, crop yield, crop waste, packaging.

Energy consumption defined energy streams
These include lighting, shading, CHP electrical power output.

Mass streams – water
This type of stream includes irrigation, services, roof-water, run off.

5 System structure

The basic structure of the program is as outlined in Figure 1 below, comprising a basic calling routine, w interfaces for user I/O and data inputs from stored files.

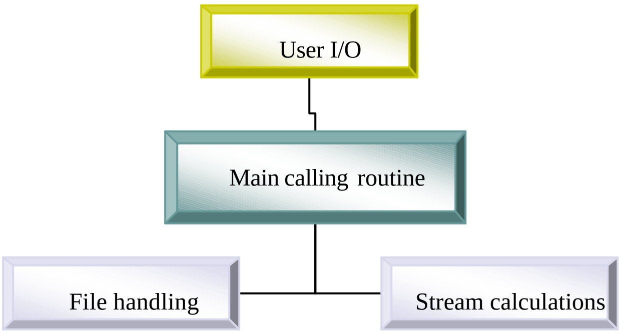


Figure 1. Basic programme structure

The main calling routine sets the input values, then calculates the energy (TH) and mass streams under th following parameters.

- Temperature integration
- Time integration
- Plant optimisation – energy sources
- Plant optimisation – energy sinks

All data results are logged in a data storage object, and this is analysed as part of the output routine. Quantitative energy streams are calculated and optimised at the end of the stream program.

Main calling routine

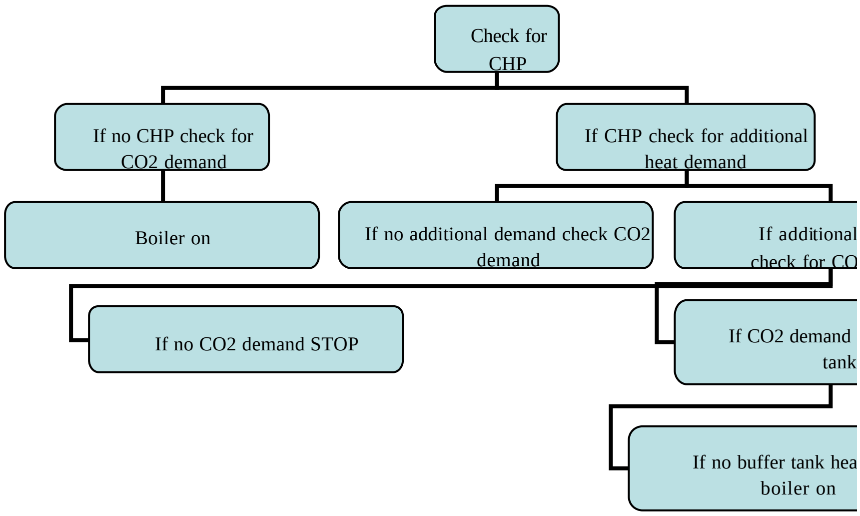
The main calling routine at present runs through the following sequence.

- Instantiate and initialise objects.
- Calculate existing theoretical energy consumptions, log results.
- Calculate theoretical minimum results with various optimization routines.
- Compare theoretical to actual results.

Calculations of the various energy streams are carried out in the flowchart function.

Flow chart

The code in this section is based on a flow chart which mimics the control strategy of an environmer computer. This is shown in the diagram below.



The main operations undertaken are as below.

- Initialise streams.
- Obtain meteorological data.
- Carry out integration.
- Calculate and set T-H energy streams
- Analyse CHP operation.
- Analyse CO_2 streams.
- Analyse buffer tank operation.
- Analyse boiler operation.
- Balance TH streams.
- Calculate and balance mass streams.

<u>Description of processes within flow chart</u>

The following summarises the main functions within each section.

T-H stream

- Calculation of structural thermal transfer stream due to radiation.
- Calculation of structural thermal transfer stream due to conduction.
- Calculation of structural thermal stream transfer due to air leakage.
- Calculation of light requirements.
- Calculation of photosynthetic activity.
- Calculation of energy stream for CO2 production.
- Stream matching – sources and sinks.

Quantitative streams

- Calculation of energy streams for inputs.
- Calculation of energy streams for outputs.
- Stream matching.

Mass stream.

- Calculation of water streams.
- Calculation of CO2 mass streams.
- Calculation of energy within mass streams.
- Stream matching – sources and sinks.

Integration

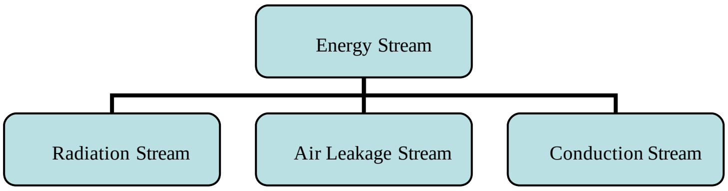
Temperature integration is modelled by specifying aggregate temperature values, time periods and d minimus values, with actual temperature data from the meteorological files used and internal results calculated accordingly.

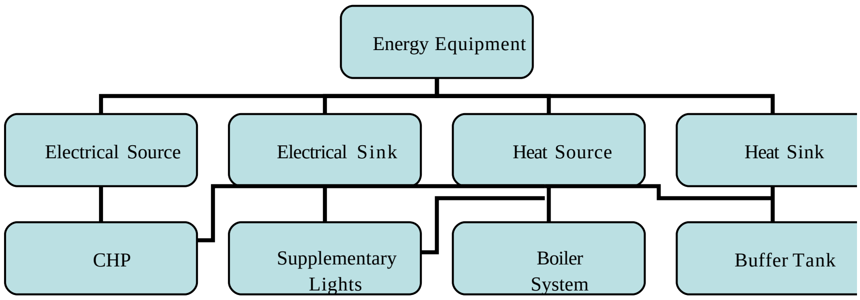
Optimisation

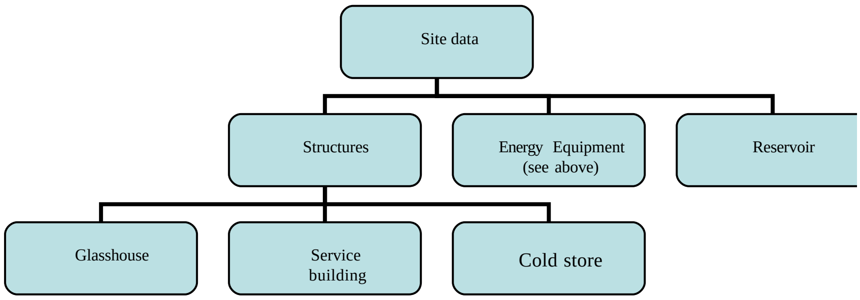
Optimisation in the demonstration version is limited, and is achieved by comparing the energy requirements of the various options, and then selecting that with the minimum (the pinch in effect). stage the optimisation routine is at a fairly basic level, but there is far greater potential for this than h been utilised so far.

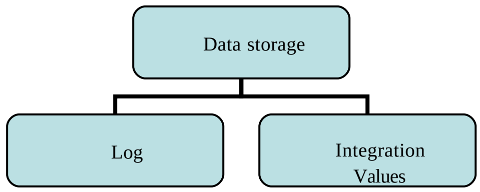
Object hierarchy

The benefits of an Object Orientated Programming style have been known for many years and are well documented. The main class hierarchies employed are outlined below. (Note that this does not include tl MFC class hierarchy employed within the I/O system, which is of a more general nature and not specific the technical development of the project.









Mass and quantitative streams are implemented on a similar basis to the above.

Data encapsulation is critical for all applications such as this one, since there is a need for onward development and compatibility. The OO approach adopted assists greatly with this, and will also aid in future developments. This can be illustrated in the Log class, which holds data from all the various runs, and an unlimited number of runs can be constructed by simple changes which promulgate through the entire programme. This will allow an AI (artificial intelligence) approach to be adopted in the future to these areas. Classes relating to other annual inputs and production outputs are generally of multiple inheritance as they relate to quantities and site / system inputs.

Input / output design
The user Input can be divided into 2 main types. Firstly annual data such as crop output figures, and secondly site specific data such as glasshouse dimensions and energy plant description. The class

"SiteDetails" is used to hold this, with internal objects derived from the associated classes for the specific elements (glasshouse, crop, boilers, buffer tanks, reservoir at this stage). Once the software has been set u for a specific site the second part will not be required, subject to infrastructure changes. In terms of the future development this allows for replication of these items with the benefits of encapsulation, thus a second glasshouse object can be created with associated dimensions, heating system, cropping etc..

The front end for manual inputting of data is designed around the conventional Windows operating syste environment, and has been programmed using the MFC library. The bulk of the data processed by the programme comprises stored data from environmental computers on site, and in the current development version file handling for accessing such data has not been taken beyond a basic calling routine for Excel .csv files.

At present the output is in the form of dialog boxes and message windows, all MFC derived, with graphic output through ChartFX, and an internally generated report.

Long term I/O development –data transfer

Many horticultural environmental computer systems offer an output for general access, often with Excel .csv format files produced. Whilst this provides one level of solution it is not ideal, and it is clear that the industry is in need of a interface protocol, and an XML based approach would appear to be a logical and universal one. The advantage of an XML approach is that there is a considerable weight of commitment it from other sectors, plus it is a reasonably robust platform which can tie in with both inputs and outputs, and also be web based for future platforms.

Results

Benchmarking may be seen to be subject to variation due to weather, yield and cropping type, as below.

Meteorological data.
The weather affects not just energy inputs but also productive output, i.e. cold weather increases energy cost, but if cold and wet then light transmission is down and thus yield will also fall.

Crop yield.
Energy use may be reduced but at the expense of yield, thus energy use per unit product may actually rise despite a decrease in site energy use. A problematic issue is that of disease, for example pepino virus in tomatoes can cause the crop to be pulled out and re-planted.

Change in cropping.
Different varieties or production systems (for example organic) will give different yields per unit are with different energy inputs. Since many growers are contracted to supermarket buyers their croppin pattern may change from year to year

Indicative figures on data collected are as below.

Ornamentals	6.4kWh per standardised 10cm pot.
Tomatoes:	10.7 – 14.5kWh/kg

The range (26%) in tomato benchmark figures shows clearly that benchmarking purely on energy per uni yield is not sufficiently robust to demonstrate energy efficiency improvements or otherwise, and the more sophisticated approach as offered by process integration will be a valuable tool to true benchmarking.

Initial data runs with the first version indicate that total site inputs are running significantly above theoretical minimums, although a degree of complexity remains to be resolved in terms of feasible operating parameters for system guidance. Realistic achievable theoretical minimum energy requirement are in the order of 60 – 75% of common levels, and theoretical minimums may be as low as 25% of curre usage depending on boundary conditions.

Conclusions

The transfer of technology into the glasshouse sector has been demonstrated to be possible, despite the complexity of inputs and more batch nature of many operations and processes. Conventional benchmark figures are too vulnerable to external inputs to be useful in all but the crudest sense. A solution based on Process Integration Technology, combining certain elements of various approaches and with novel solutions to other problems has been developed, and preliminary indications with limited data sets show that that theoretical minimum energy inputs are substantially lower than current ones, with achievable levels being 60 -75% of current.

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