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Integrated production and utility system approach for optimizing industrial unit operations

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ABSTRACT

To meet utility demands some industrial units use onsite utility system. Traditionally, the management of such type of industrial units is carried out in three sequential steps: scheduling of the manufacturing unit by minimizing inventory, estimating the utility needs of manufacturing unit and finally operation planning of the utility system. This article demonstrates the value of an integrated approach which couples the scheduling of manufacturing unit with operational planning of the utility system. A discrete-time mixed integer linear programming (MILP) model is developed to compare traditional and integrated approaches. Results indicate that the integrated approach leads to significant reduction in energy costs and at the same time decreases the emissions of harmful gases.

Keywords:
Scheduling
CHP plant
Utility management
MILP
Energy cost

1. Introduction

The industrialization in developing countries and especially that of China and India will increase the global energy demand. In developing countries, the proportion of global energy consumption is projected to increase from 46 to 58 percent between 2004 and 2030, at an average annual growth rate of 3 percent. During the same period, industrialized nations will witness an annual growth in the demand for energy of 0.9 percent [1].

The industrial sector accounts for one third of global energy consumption. Although processes used in the industrial sector are highly diverse, a common feature to all is their reliance on fossil fuels as the primary source of energy. A large part of the energy consumption of the industrial unit is focused on the production of utilities. A utility is defined as any quantity which has high energy and can be useful to an industrial unit in manufacturing the finished product. The utility can be in the form of electricity, steam (at various pressure levels), hot/cold water or hot air.

The reliance on fossil fuels as the primary source of energy has a huge negative impact on the environment and eco-system of our planet. The studies of the Intergovernmental Panel for Climate Change (IPCC) have acknowledged that the main cause for the phenomenon of global warming is the emission of greenhouse gases, which are released into the atmosphere during burning of fossil fuel. Global warming is considered to be the biggest impediment in carrying out sustainable development.

Consequently, there is a concentrated effort in the scientific world to find alternative sources of energy. Current emphasis is on renewable energies such as wind, solar, hydrogen, etc. However, even by the most optimistic assessments, all these alternatives are long-term solutions. The projections of the Energy Information Administration (EIA), a statistical agency of the American department of energy, show that fossil fuels will remain as primary sources of energy in the immediate future. Thus, along with finding alternative energy sources, an effort must be made to look for ways of conserving energy that will minimize the damage caused by the use of fossil fuels [2]. Initiatives like cleaner production [3] and zero-emissions [4] are important approaches in this regard. However a short-term solution, which has been identified by the IPCC, is to improve energy efficiency in industrial processes [5]. This can be achieved by two possible means; firstly, advancements in energy generation technology and secondly, the use of methodologies such as 'process integration'.

Combined heat and power (CHP) is an important energy production technology as it improves the overall energy efficiency of the process while simultaneously reducing greenhouse gas emissions, especially that of CO_2 [6]. CHP, also known as the 'cogeneration process', relies on the simultaneous generation of electricity and other forms of useful thermal energy (steam or hot water) for manufacturing processes or central heating systems. The energy savings and

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Nomenclature

Indices

i	fuels
j	units (processing equipments /boilers/turbines)
k	tasks
q	piecewise segment of efficiency curve
s	states
t	time period
v	utility

Sets

$BOIL$	set of boilers in CHP plant
$FUEL$	set of fuels in CHP plant
J	set of processing equipments in manufacturing unit
K	set of tasks
K_s^{cons}	set of task k which consume state s
K_s^{prod}	set of task k which produce state s
S	set of states
$TURB$	set of turbines in CHP plant
$UTILITY$	set of utilities provided by CHP plants; {LP, MP, HP, electricity}

Parameters

a_j	consumption coefficient for MP steam redirected towards boiler
b_j	consumption coefficient for electricity required to carry out boiler operation
cc_i	calorific value of fuel (MJ/kg)
cf_i	cost of fuel (€/ton)
CEL	electricity purchase cost (€/MWh)
$CGHG$	cost incurred for emissions of GHG (€/ton)
$Cop_{v,k}$	utility v consumed for task k (ton/hr of steam or MW/hr of electricity required per ton of material processed)
$CSOX$	cost incurred for emissions of SO_x (€/ton)
cpt_i	capacity of storage repository for fuel i (tons)
ghg_i	coefficient of GHG released from boiler due to fuel i
$ehst_i$	exhaust steam parameter for turbine j (defined as a fraction of $TXHP_{t,j}$)
h	enthalpy values based on steam temperature and pressure (MJ/kg)
$Imax_{j,i}$	quantity of fuel i that is required to attain maximum steam level in boiler j
$Imin_{j,i}$	quantity of fuel i that is required to attain minimum steam level in boiler j
$\bar{I}_{q,j,i}$	fuel threshold of the piecewise efficiency curve segment q
I_s	inventory coefficient for state s that is used to obtain the tardiness starting date
p_k	time duration for executing task k in the unit j
Q	total number of piecewise segments
$SIdem_{j,i}$	quantity of fuel i that is used during starting-up phase of boiler j
sox_i	coefficient of SOx released from boiler due to fuel i
ssf_i	safety stock parameter for fuel i (defined as a fraction of cpt_i)
T	time horizon
$TXHPmax_{t,j}$	maximum amount of steam that can enter turbine j in time period t
$TXHPmin_{t,j}$	minimum amount of steam that can enter turbine j in time period t
$XHPmax_j$	maximum amount of steam that can be produced by boiler j
$XHPmin_j$	minimum amount of steam that can be produced by boiler j
$\overline{XHP}_{q,j,i}$	steam threshold of the piecewise efficiency curve segment q
$\eta_{j,i}$	efficiency of boiler j with fuel i
η_j	efficiency of the turbine j
C_s, C_s^{max}	storage capacity and the maximum storage capacity of state s (tons)
$V_{k,j}^{min}, V_{k,j}^{max}$	minimum and maximum size of processing equipment j when processing task k (tons)
$\rho_{k,s}^{cons}, \rho_{k,s}^{prod}$	proportion of state s consumed or produced by task k

Binary variables

$A_{q,t,j,I}$	to determine the boiler efficiency as a function of boiler load factor
$W_{k,j,t}$	to determine whether task k is being carried out in unit j in time period t
$SB_{t,j,i}$	to determine whether boiler j is operational during time period t using fuel i
$FSB_{t,j,i}$	to determine whether boiler j is being restarted during time period t using fuel i

environmental benefits offered by CHP make it an ideal candidate for use in the building sector (district heating) [7] and in industrial units [8]. Both the United Nations [9] and the European Union [10] see CHP as one of the very few technologies that can offer a short or medium-term solution for pollution control by increasing energy efficiency.

CHP is a popular choice for several onsite industrial utility systems, which are a feature of many chemical and petrochemical plants. However, in the majority of these industrial sites "production is the king" and utility systems are regarded mainly as a support function whose objective is to provide service to the manufacturing unit. Due to this biased outlook the utility systems fail to attain their full energy efficiency potential. Technological advancement and breakthroughs in the development of more energy efficient plant machinery is an ongoing process. However, an industrial process is constrained by thermodynamic, kinetic and transport limitations. Thus, in addition to technological advancements in plant machinery, one also needs to address the concept of process integration [11]. In the past, process integration was synonymous with the thermodynamic technique of 'pinch and energy analysis'. Nowadays, process integration techniques cover four major areas. Firstly, the efficient use of raw materials, secondly, emission reduction, thirdly, process operations and of course energy efficiency [12]. Process integration has evolved over the years and now makes significant use of mathematical methods and optimization models.

The objective of this article is to develop an approach where the production process and the utility system will be integrated. The remainder of the paper is organized as follows. Section two outlines the problem statement. A mathematical model indicative of the traditional (sequential) approach and the new (integrated) approach is presented in section three. Section four compares the two approaches by applying the model to three different industrial units. Finally, on the basis of all the data, the conclusions and future outlook are presented in section five.

2. Problem statement

Traditionally the industrial sector has been reliant on *utility suppliers* for the supply of electricity while it generates other utilities

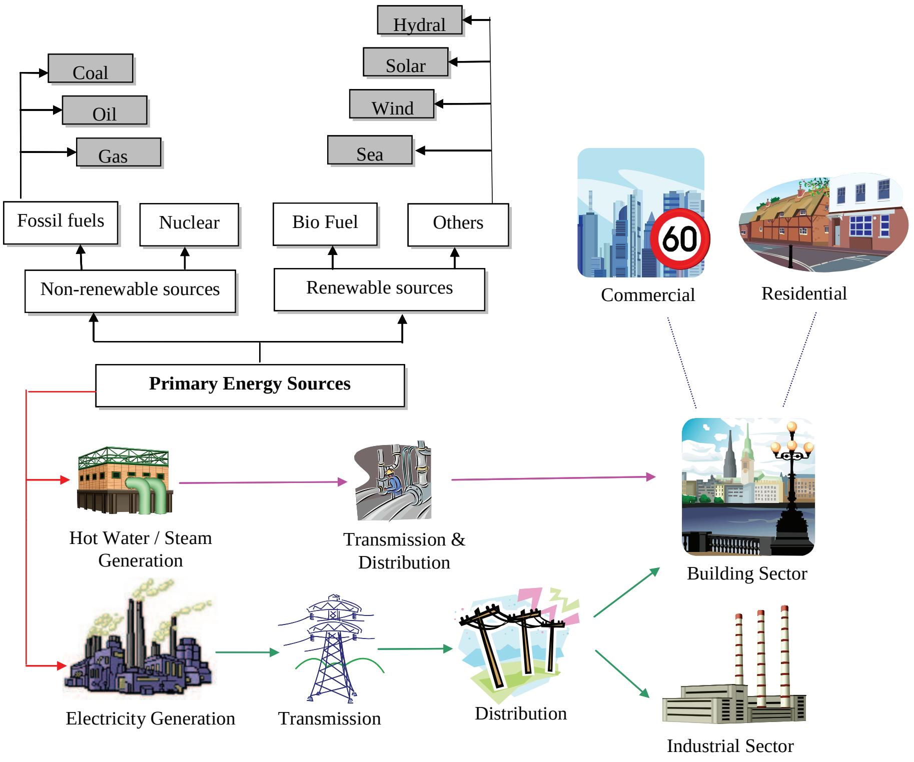

Fig. 1. Utility supply structure.

on its own (see Fig. 1). Plant machinery, such as boilers, condensers, compressors etc, is used for this purpose. However, there is a growing tendency for high-energy intensive industries to produce their own electricity. The terminology used for such industrial processes is *auto-production*. This refers to electricity, heat or steam produced by an industrial facility for its own consumption or in order to sell to other consumers or to the electricity grid.

It can be assumed that an industrial unit using auto-production comprises of two units, a *utility system* that uses fuels to generate utilities and a *manufacturing unit*, which consumes these utilities to produce the finished product. Utilities generated in the utility system have a direct correlation with the activity level in the manufacturing unit. This relationship between the manufacturing unit and utility system can be established by using mathematical optimization, which cannot only help in design and retrofit aspects but it can also aid in solving the daily operational problems. The scope of this study will be limited to the operational aspect, with no structural modifications in the industrial unit.

The traditional approach to auto-producer scheduling is dependent on the sequential resolution of three sub-problems (Fig. 2):

- First of all 'task scheduling' is carried out in the manufacturing unit, which, based on the production recipes, allocates limited resources (processing equipments) to produce the final

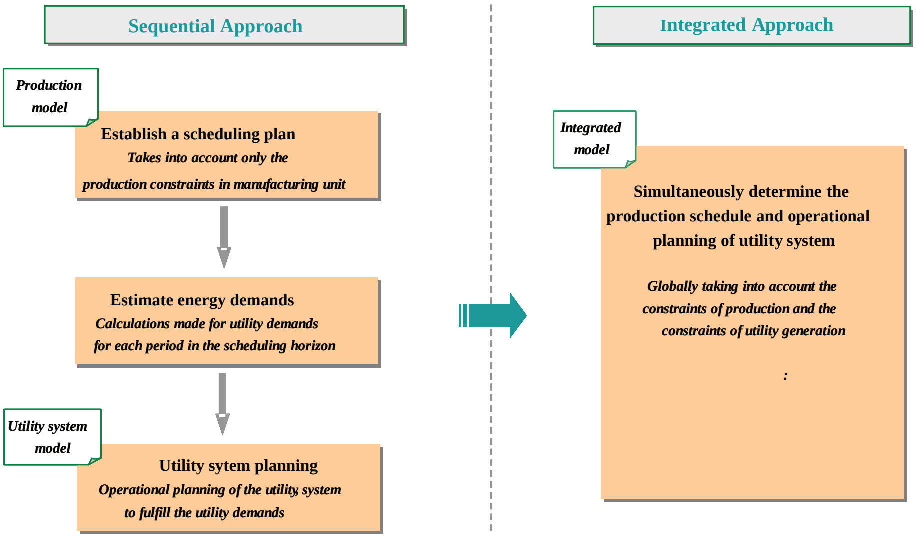

Fig. 2. Comparison between sequential and integrated approach.

product(s). Task scheduling determines the number of tasks, the timing of these tasks and the batch size of each task to be performed in the manufacturing unit. The objective is to minimize the make-span or inventory.
- Subsequently, on the basis of the task scheduling, the overall utility demands for the manufacturing unit are estimated. In these calculations the concept of energy integration [13] and especially that of pinch analysis [14] can be used to develop a heat exchange network that minimizes the utility demands in the manufacturing unit.
- Finally, knowing the utility demands, the final step is the operational planning of the utility system. The objective in this step is to operate the utility system in such a manner that it not only meets the utility demands of the manufacturing unit but also minimizes the energy costs [15].

In the sequential approach the relationship between the manufacturing unit and the utility system is that of 'master and slave'. As pointed out by Adonyi et al. [16], the utility demands are strongly dependent on the first step of the manufacturing unit, task scheduling. As a consequence, the operational planning of the utility system and the subsequent energy costs are heavily reliant on the outcome of the task scheduling. In spite of this direct correlation, task scheduling does not take into account the operational planning of the utility system. This lukewarm approach towards not taking into account the utility system in the overall considerations can perhaps be explained by the low price of fossil fuels. However, over the last few years increased fuel costs have meant that considering the utility system as a subsidiary function is no longer feasible. On the other hand, if the operational planning of the utility system is carried out first then it generally leads to infeasibilities at the task scheduling level of the manufacturing unit. Hence, the traditional sequential approach inevitably leads to a non-optimized energy cost.

The task scheduling aspect of the manufacturing unit has been subject to extensive research. However, few scheduling models have been proposed in which the management of utilities is explicitly taken into account. For example, Kondili et al. [17] developed a model to determine a plan for minimizing manufacturing costs. The cost of energy was assumed to vary during the day and energy consumption was dependent on the nature of the product manufactured and the equipment used. The impact of energy costs was catered by positioning energy costs in the objective function. This model was further enhanced [18] to develop a short-term batch scheduling algorithm which incorporated the limited availability of the utilities as a *scheduling resource constraint*.

It should be noted that unlike the resources classically considered in the scheduling problems (machinery or work force), utilities have special characteristics which must be taken into account. Utilities are a more versatile resource and are present in various forms (steam at different pressures, electricity, hot water, etc). Utilities are also resources that are difficult to store in their ultimate form. Some recent studies have taken into consideration these peculiarities of utilities. Behdani et al. [19] developed a continuous-time scheduling model, which included the constraints related to the production, availability and consumption of different types of utilities (water cooling, electricity and steam). Hait et al. [20] presented an approach designed to minimize the energy costs of a foundry, subject to the specific provisions relating to the power pricing and market-based strategies for load shedding. However, in all these approaches, the focus is primarily on the manufacturing unit while the utility system is modeled in an aggregated manner. Moreover, the operational planning aspect of the utility system is not considered in these models.

Conversely, research on the utility system has concentrated exclusively on setting up boilers, turbines and steam distribution network. The process user, that is, the manufacturing unit, is not taken into consideration. A thermodynamic based heuristic method was used by Nisho et al. [21] to design a steam power plant. Grossman and Santibanez [22] presented a mathematical modeling based approach using Mixed Integer Linear Programming (MILP) for process synthesis. The design of a utility plant using the concept of 'superstructure' was developed by Papoulias and Grossmann [23] using MILP. Subsequent research in this area resulted in more complex and multi-period MILP models [24–26].

The objective of all these models was to design a utility system that satisfies specific power and steam demands. Similarly, the models dealing with the operational planning of utility systems concentrate uniquely on reducing the energy costs without considering the task scheduling of the manufacturing unit. For example, Marik et al. [27] used a combination of forecasting and optimization methods to devise an effective decision-making tool for the management of utility systems. The forecasting methods determine the most probable demands based on the historical data and optimization methods seek a more efficient operational regime. De et al. [28] developed an artificial neural network (ANN) model to monitor the performance of the CHP based utility system. Soylu et al. [15] developed a multi-period MILP model for collaboration between CHP plants located at different industrial sites. The objective of the model was to fulfill the utility demands in a multi-site environment. However, the utility demands during each time interval were assumed to be given a priori. In each of the above mentioned models no provision is made for sudden changes in consumer demands, which might alter with varying activity levels in a manufacturing unit. Therefore, for efficient operations of industrial units there is a need to correlate the short-term scheduling of manufacturing unit with the operational planning of utility system.

Even though this aspect has largely been ignored over the years, some recent research has focused on developing models and methods that try to incorporate aspects of task scheduling and operational planning of utility system. Puigjaner [29] presented a detailed framework for heat and power integration into batch and semi-continuous processes. Moita et al. [30] developed a dynamic model, combining a salt crystallization processing unit and a cogeneration unit. Zhang and Hua [31] developed a model for determining the MILP optimum operating points of a refinery coupled with a cogeneration unit.

In this study an integrated approach is presented, which like its counterpart sequential approach, gives paramount importance to meeting the product demands. However, the integrated approach directly incorporates the aspect of operational planning of the site utility system into the task scheduling problem of the manufacturing unit. This results in better synchronization between the manufacturing unit and site utility system, thereby maximizing the energy efficiency of the whole industrial unit.

3. Mathematical model

The constraints of the mathematical model are provided by applying production and capacity constraints along with mass and energy balances to all the components of the industrial unit. Simplifying assumptions make it possible to use linear equations and binary variables to model the behavior of the main components of an industrial unit. A discrete time-based MILP model is developed to formulate the problem. The model is divided into T ($t = 1 \ldots T$) one-hour periods representing multi-period operations of the industrial unit. The nomenclature given at the end provides the definition of each parameter and variable used in the model.

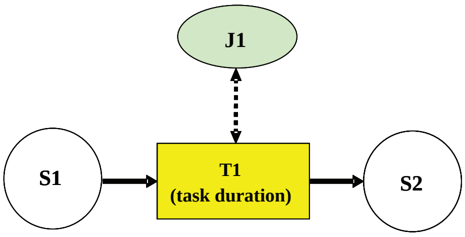

Fig. 3. Basic RTN representation.

3.1. *Manufacturing unit model*

The manufacturing unit employs production recipes via processing equipments to turn the raw materials into intermediate and finished products. The manufacturing unit is characterized by the Resource Task Network (RTN) representation [32,33], a bipartite graph comprising of two types of nodes: resources (denoted by a circle) and tasks (denoted by a square). The concept of 'resource' is entirely general and includes all entities that are involved in the process steps, such as materials (raw materials, intermediates and products), processing and storage equipment (tanks, reactors, etc.) and utilities (operators, steam, etc.). A 'task' is defined as an operation that transforms a certain set of resources into another set.

To simplify the graphical representation, the resource node is sub-divided into a state node and an equipment node (Fig. 3). The state node (the circle) is used for depicting materials and the equipment node (the oval) is used to portray processing equipment. It is assumed that the state nodes also act as storage areas for the material. The operating times of each task are supposed as known and independent of the batch size. The constraints of the model are as follows:

3.1.1. *Allocation constraints*

At a given time t, processing equipment j can, at the most, initiate one operation. In addition, if an operation (task) k is launched in period t ($W_{k,j,t} = 1$) then this processing equipment j shall no longer be available ($W_{k,j,t'} = 0$) during the periods $t' = t - p_k + 1$ till $t' = t + p_k - 1$ (i.e. duration of the task). This is expressed by Eq. (1):

$$\sum_{k\in K_j} \sum_{\substack{t' = t - p_k + 1 \\ t > 0}}^{t} W_{k,j,t'} \le 1 \quad \forall j\in J, \forall t = 1,..,T \tag{1}$$

3.1.2. *Material balance*

Eq. (2) shows that the amount of material in state s during period t is the difference between the quantity of the material produced and that consumed. The initial stocks $S0_s$ are supposed known and no task k is launched before period $t > p_k$.

$$S_{s,t} = S_{s,t-1} + \sum_{k\in K_s^{\mathrm{prod}}} \rho_{k,s}^{\mathrm{prod}} \sum_{\substack{j\in J_k \\ t > p_k}} B_{k,j,t-p_k} - \sum_{k\in K_s^{\mathrm{cons}}} \rho_{k,s}^{\mathrm{cons}} \sum_{j\in J_k} B_{k,j,t}0 - D_{s,t} \quad \forall s\in S, \forall t = 1,..,T \tag{2}$$

$$S_{s,0} = S0_s \quad \forall s\in S \tag{3}$$

3.1.3. *Capacity constraint*

Eqs. (4) and (5) represent the production capacity and storage limitation constraints of the processing equipment j.

$$W_{k,j,t} V_{k,j}^{\mathrm{min}} \le B_{k,j,t} \le W_{k,j,t} V_{k,j}^{\mathrm{max}} \quad \forall k\in K, \forall j\in J, \forall t = 1,..,T \tag{4}$$

$$0 \le S_{s,t} \le C_s^{\mathrm{max}} \quad \forall s\in S, \forall t = 1,..,T \tag{5}$$

3.2. *Utility system model*

A typical CHP based utility system comprises of fuel storage tanks, boilers for high pressure steam production, steam turbines for electricity generation, valves for reducing pressure and mixing equipment for mixing likewise material (Fig. 4).

3.2.1. *Fuel storage model*

The amount of fuel i entering the boiler j and producing HP steam in the period t is represented by $I_{t,j,i}$. Each fuel repository has a certain capacity and initial amount of fuel $ORF_{0,i}$ stored in it is assumed as known. To simplify the fuel storage model in this study it is assumed that the fuel inventory is sufficient to meet utility requirements and no fuel purchase is required. It is further assumed that there are no holding costs incurred for the fuel storage.

$$ORF_{t,i} = ORF_{t-1,i} - \sum_{j\in BOIL} (I_{t,j,i} + SI_{t,j,i}) \quad \forall i\in FUEL, \forall t = 1,..,T \tag{6}$$

$$cpt_i \ge ORF_{t,i} \ge ssf_i \cdot cpt_i \quad \forall i\in FUEL, \forall t = 1,..,T \tag{7}$$

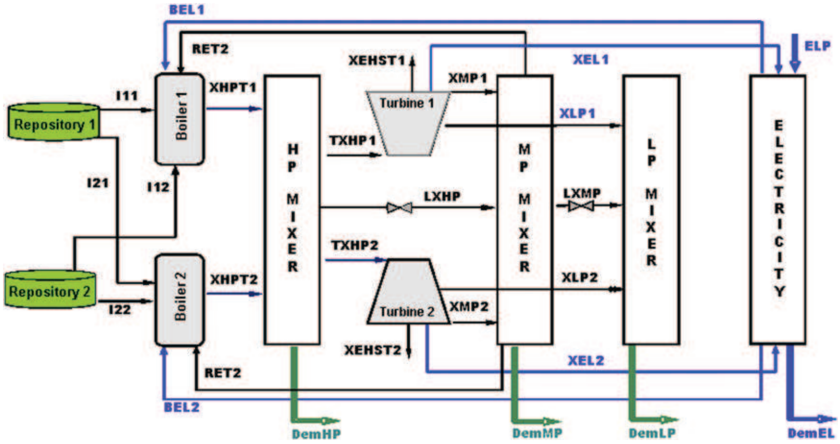

Fig. 4. Typical CHP based Utility System.

The Eq. (6) models the fuel tank mass balance. Fuel leaving the repository depends on the demands of the boiler. However, as enforced by Eq. (7), the quantity of fuel in the repository can neither fall below the safety stock limit nor exceed the maximum capacity.

3.2.2. Boiler model

It is assumed that boiler *j* has an uninterrupted supply of air and water. The fuel type *i* is supplied to the boiler where it is burnt to generate high pressure (HP) steam. The boiler requires a certain amount of medium pressure steam (to pre-heat water) and electricity to carry out its operations. Although multi-fuel fired boiler operation is considered, during time period *t* only one type of fuel is used in the boiler. The boiler equations can be subdivided into four broad categories.

i. Associating fuel consumption with steam production

Eq. (8) models the fuel consumption in boiler *j* as a function of the amount of high pressure (HP) steam produced, calorific value of fuel, boiler efficiency and the enthalpy difference between superheated steam and feed-water heaters. This is essentially a nonlinear equation but simplifying assumptions are used to develop a representative linear equation. It is assumed that steam pressures and temperatures are fixed at the boiler inlet and exit, thus turning the enthalpy difference into a parameter. However, there are still two variables in the equation, boiler efficiency $\eta_{j,i}$ and fuel consumption $\bar{I}_{q,j,i}$.

$$\bar{I}_{q,j,i} = \frac{\left(h_b - h_{fw}\right)\cdot\overline{XHP}_{q,j,i}}{cc_i\cdot\eta_{q,j,i}} \qquad \forall q\in Q,\ \forall j\in BOIL,\ \forall i\in FUEL \tag{8}$$

Soylu et al. [15] solved this problem by using the assumption that boiler efficiency remained constant irrespective of load factor. However, boiler efficiency is significantly less when it operates at part load, i.e. operating at less than design capacity. In order to include the effect of the efficiency variation with the varying load factor and at the same time guarding the condition of linearity, *piecewise linear approximation* is used (Fig. 5). For this study three linear pieces are considered ($Q = 3$), where:

$$\overline{XHP}_{0,j,i} = XHP\text{min}_j;\ \ \overline{XHP}_{1,j,i} = 0.5\cdot XHP\text{max}_j;$$
$$\overline{XHP}_{2,j,i} = 0.75\cdot XHP\text{max}_j \quad \text{and} \quad \overline{XHP}_{3,j,i} = XHP\text{max}_j$$

Eqs. (9)–(11) develop this piecewise linear approximation curve, quantifying fuel consumption with the varying load factor. $XHPmin_j$ is the minimum amount of steam that can be produced by the boiler. Below this steam level, it is not economically viable to operate the boiler and hence, it is shutdown. Eq. (9) determines the amount of HP steam being generated in the boiler. It joins q linear equations by use of binary variables $A_{q,t,j,i}$ and continuous variables $x_{q,t,j,i}$. The $XHP_{t,j,i}$ amount of steam produced in the boiler is determined by the numerical value of these binary and continuous variables.

$$XHP_{t,j,i} = \sum_{q=1}^{Q} A_{q,t,j,i}\overline{XHP}_{q-1,j,i} + x_{q,t,j,i}\left(\overline{XHP}_{q,j,i} - \overline{XHP}_{q-1,j,i}\right) \quad \forall t = 1,..,T,\ \forall j\in BOIL,\ \forall i\in FUEL \tag{9}$$

Eq. (10) models the amount of fuel type *i* consumed in the boiler to generate $XHP_{t,j,i}$ amount of steam.

$$I_{t,j,i} = \sum_{q=1}^{Q} A_{q,t,j,i}\bar{I}_{q-1,j,i} + x_{q,t,j,i}\left(\bar{I}_{q,j,i} - \bar{I}_{q-1,j,i}\right) \quad \forall t = 1,..,T,\ \forall j\in BOIL,\ \forall i\in FUEL \tag{10}$$

Eq. (11) enforces that, at maximum, only one binary variable $A_{q,t,j,i}$ will have the value “1”, while Eq. (12) limits the value of continuous variable $x_{q,t,j,i}$ between 0 and 1. Eq. (13) imposes a further restriction whereby during a particular time period, only one type of fuel can be burnt in the boiler.

$$\sum_{q=1}^{Q} A_{q,t,j,i} \le 1 \qquad \forall t = 1,..,T,\ \forall j\in BOIL,\ \forall i\in FUEL \tag{11}$$

$$0 \le x_{q,t,j,i} \le A_{q,t,j,i} \quad \forall q\in Q,\ \forall t = 1,..,T,\ \forall j\in BOIL,\ \forall i\in FUEL \tag{12}$$

$$\sum_{i\in FUEL} A_{q,t,j,i} \le 1 \qquad \forall q\in Q,\ \forall t = 1,..,T,\ \forall j\in BOIL \tag{13}$$

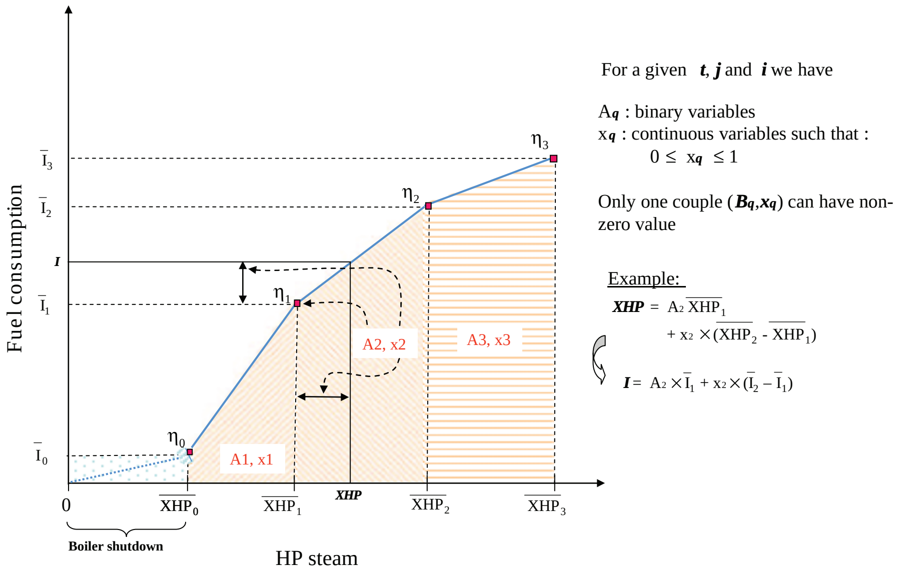

Fig. 5. Fuel consumption as a function of HP steam generated in boiler.

Table 1
Boiler Shutdown.

SB_{t-1}	SB_t	SB_{t+1}
0	0	≤1
0	1	≤1
1	0	0
1	1	≤1
0	0	≤1

ii. Boiler shutdown and restart constraints

Boiler operations are not instantaneous and it is assumed that the boiler takes one hour (equivalent to one time period) to shutdown and also, one hour to restart. Thus, once the boiler is shutdown, it will require a minimum of two hours before it can start generating steam again. During the restart phase, the boiler uses $SIdem_{t,j,i}$ amount of fuel without producing any steam.

Eq. (14) confines the amount of HP steam that can be produced by the boiler during its operational phase (i.e. when $SB_{t,j,i} = 1$) and makes it zero when the boiler is in the shutdown state (when $SB_{t,j,i} = 0$).

$$XHP\mathrm{min}_j \cdot SB_{t,j,i} \leq XHP_{t,j,i} \leq XHP\mathrm{max}_j \cdot SB_{t,j,i} \quad \forall t = 1,..,T,\ \forall j \in BOIL,\ \forall i \in FUEL \tag{14}$$

Eq. (15) determines that boiler being operational in the future time period depends on the current state of the boiler as well as the state of boiler in the previous time interval (cf. Table 1).

$$SB_{t+1,j,i} \leq SB_{t,j,i} + (1 - SB_{t-1,j,i}) \quad \forall t = 2,..,T-1,\ \forall j \in BOIL,\ \forall i \in FUEL \tag{15}$$

Eqs. (16) and (17) establish that 'boiler restart' in a given time interval will occur only if it is operational in the future period and it is not operational in the current time interval. (cf. Table 2)

$$FSB_{t+1,j,i} \leq SB_{t+1,j,i} \quad \forall t = 1,..,T-1,\ \forall j \in BOIL,\ \forall i \in FUEL \tag{16}$$

$$FSB_{t+1,j,i} \geq SB_{t+1,j,i} - SB_{t,j,i} \quad \forall t = 1,..,T-1,\ \forall j \in BOIL,\ \forall i \in FUEL \tag{17}$$

Fuel consumed during the restart phase without producing steam is represented by Eq. (18). It is important to note that the presence of $SI_{t,j,i}$ in the objective function (Crit. 2) makes it mandatory for boiler restart to occur only when it is absolutely necessary, i.e. preferably $FSB_{t,j,i} = 0$.

$$SI_{t,j,i} = FSB_{t,j,i} \cdot SIdem_{j,i} \quad \forall t = 1,..,T,\ \forall j \in BOIL,\ \forall i \in FUEL \tag{18}$$

Eqs. (19) and (20) are limiting constraints, enforcing that only one fuel can be used to restart the boiler and similarly, only one fuel can be used during the operation of the boiler.

$$\sum_{i \in FUEL} FSB_{t,j,i} \leq 1 \qquad \forall t = 1,..,T,\ \forall j \in BOIL \tag{19}$$

Table 2
Boiler Startup.

SB_{t-1}	SB_{t+1}	FSB_t
0	0	0
0	1	1
1	0	0
1	1	≤ 1 → 0 by criteria
0	0	0

$$\sum_{i \in FUEL} SB_{t,j,i} \leq 1 \quad \forall t = 1,..,T,\ \forall j \in BOIL \tag{20}$$

iii. Emission constraints

Eqs (21) and (22) model the amount of SO_x and greenhouse gas (*GHG*) emissions from the boiler.

$$XSOX_{t,j} = \sum_{i \in FUEL} sox_i \cdot (I_{t,j,i} + SI_{t,j,i}) \ \forall t = 1,..,T,\ \forall j \in BOIL \tag{21}$$

$$XGHG_{t,j} = \sum_{i \in FUEL} ghg_i \cdot (I_{t,j,i} + SI_{t,j,i}) \ \forall t = 1,..,T,\ \forall j \in BOIL \tag{22}$$

iv. Boiler electricity and steam return constraints

The amount of medium pressure heat redirected back to preheat water and electricity used by the feed water pump to inject water into the boiler are modeled by Eqs. (23) and (24).

$$RET_{t,j} = a_j \cdot \sum_{i \in FUEL} XHP_{t,j,i} \quad \forall t = 1,..,T,\ \forall j \in BOIL \tag{23}$$

$$BEL_{t,j} = b_j \cdot \sum_{i \in FUEL} XHP_{t,j,i} \quad \forall t = 1,..,T,\ \forall j \in BOIL \tag{24}$$

3.2.3. *Turbine model*

In this study, it is assumed that multi-stage back pressure steam turbines are used for the purpose of electricity generation. The whole functioning of the multi-stage steam turbine is presented in Fig. 6. The *high pressure steam* comes into the first stage of the turbine where it expands and ultimately leaves as medium pressure steam. This *medium pressure steam* then enters the second turbine stage and leaves as low pressure steam. Finally the *low pressure steam* enters the third stage of the turbine and exits at a very low pressure. This 'exhaust steam' is above the saturated steam level but it is not fit to meet the process requirements of the manufacturing unit.

After each stage, some quantities of medium pressure (MP) and low pressure (LP) steam are extracted from the turbine to meet the steam demands of the manufacturing unit. Another source for meeting MP and LP steam demands is by expanding the steam through pressure release valves (PRVs).

Eq. (25) models the turbine mass balance.

$$TXHP_{t,j} = XMP_{t,j} + XLP_{t,j} + XEHST_{t,j} \ \forall t = 1,..,T,\ \forall j \in TURB \tag{25}$$

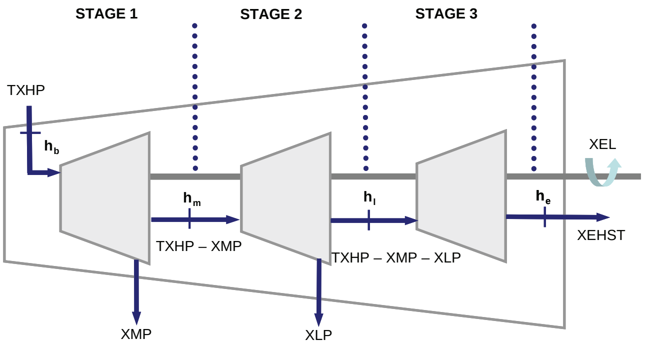

Fig. 6. Functioning of a multistage turbine.

Eq. (26) places limiting constraint on quantity of steam that can be extracted from the turbine.

$$XEHST_{t,j} \geq ehst_j \cdot TXHP_{t,j} \quad \forall t = 1,..,T, \forall j \in TURB \tag{26}$$

Eq. (27) is also a limiting constraint which quantifies the amount of steam entering the turbine.

$$TXHP\min_{t,j} \leq TXHP_{t,j} \leq TXHP\max_{t,j} \quad \forall t = 1,..,T, \forall j \in TURB \tag{27}$$

Eq. (28) furnishes the turbine energy balance which quantifies the electricity generated by the turbine. To obtain Eq. (28), it is assumed that the kinetic and potential energy effects are negligible in the turbine and that the turbine operates adiabatically. It is further assumed that the steam pressure and temperatures at each stage of the turbine are known and finally that the turbine efficiency η_j remains constant.

$$\begin{aligned} XEL_{t,j} = \eta_j \cdot \big[& TXHP_{t,j} \cdot (h_b - h_m) + (TXHP_{t,j} - XMP_{t,j}) \cdot (h_m - h_l) \\ & + (TXHP_{t,j} - XMP_{t,j} - XLP_{t,j}) \cdot (h_l - h_e) \big] \ \forall t \\ & = 1,..,T, j \in TURB \end{aligned} \tag{28}$$

3.2.4. Mixer model

Mixers are hypothetical devices and are only used to achieve the material balance of *HP*, *MP* and *LP* steam. Eqs. (29)–(31) provide the mass balance of the *HP*, *MP* and *LP* steam respectively.

$$\sum_{i \in FUEL} \sum_{j \in BOIL} XHP_{t,j,i} - LXHP_t - \sum_{j \in TURB} TXHP_{t,j} \geq DemHP_t \quad \forall t = 1,..,T \tag{29}$$

$$LXHP_t + \sum_{j \in TURB} XMP_{t,j} - LXMP_t - \sum_{j \in BOIL} RET_{t,j} \geq DemMP_t \quad \forall t = 1,..,T \tag{30}$$

$$LXMP_t + \sum_{j \in TURB} XLP_{t,j} \geq DemLP_t \quad \forall t = 1,..,T \tag{31}$$

Eq. (32) models the amount of electricity generated onsite and the electricity purchased from an external source:

$$\sum_{j \in TURB} XEL_{t,j} + ELP_t \geq DemEL_t + \sum_{j \in BOIL} BEL_{t,j} \quad \forall t = 1,..,T \tag{32}$$

3.3. Coupling manufacturing unit and utility system

Each task that is performed in the manufacturing unit requires a certain amount of energy, which is provided by one or more types of utilities. The flow of utilities from the utility system to the manufacturing unit provides the link between the two units. The overall utility consumption can be calculated using the Eqs. (33) and (34). The variable $TBatch_{k,t}$ represents the total batch size of task k in period t and $CGlob_{v,t}$ represents the overall utility.

$$TBatch_{k,t} = \sum_{j \in J_k} \sum_{\substack{t' = t - p_k + 1 \\ t > 0}}^{t} B_{k,j,t'} \quad \forall k \in K, \forall t = 1,..,T \tag{33}$$

$$CGlob_{v,t} = \sum_{k \in K} Cop_{v,k} TBatch_{k,t} \quad \forall v \in UTILITY, \forall t = 1,..,T \tag{34}$$

3.4. Comparison of sequential and integrated approaches

3.4.1. Sequential approach

The sequence of steps followed in this approach is as follows:

a) Establishing a manufacturing schedule by taking into account only the production requirements, (Eqs. (1)–(5)). The criterion used for this purpose is tardiness, i.e. minimization of the inventory level.

$$C_{stock} = \sum_{t=1}^{T} \sum_{s \in S} l_s \cdot S_{s,t} \tag{Crit. 1}$$

b) On the basis of the manufacturing plan Eqs. (33) and (34) are used to estimate utility requirements. The utility requirements are classified as steam and electricity demands according to following equations:

$$Dem_{v,t} = CGlob_{v,t} \quad \forall v \in UTILITY, \forall t = 1,..,T \tag{35}$$

c) Finally, on account of the estimated utility demands, the planning for the CHP plant is carried out (Eqs. (6)–(32)). The criterion used for the CHP planning is the minimization of operational costs comprising of fuel cost, electricity purchase cost and penalty cost incurred due to the emission of harmful gases.

$$\begin{aligned} COST = & \sum_{t}^{T} \sum_{j \in BOIL} \sum_{i \in FUEL} cf_i \cdot (I_{t,j,i} + SI_{t,j,i}) + \sum_{t}^{T} ELP_t \cdot CEL \\ & \sum_{t}^{T} \sum_{j \in BOIL} XSOX_{t,j} \cdot CSOX + \sum_{t}^{T} \sum_{j \in BOIL} XGHG_{t,j} \cdot CGHG \end{aligned} \tag{Crit.2}$$

3.4.2. Integrated approach

The integrated approach tries to overcome the drawbacks in the sequential approach. Rather than considering the manufacturing unit and utility system as separate entities, the integrated approach regards them as a single unit by concurrently solving Eqs. (1)–(35). The optimization criteria taken into account is the minimization of operational energy costs, which is the same as represented in Eq. (Crit. 2). Thus, while evaluating task scheduling the integrated approach incorporates and cross checks for the availability of utilities. In that way, it simultaneously carries out both the task scheduling of the manufacturing unit and the operational planning of the utility system. This ends the *master-slave* relationship between the two units and leads to more optimum production scheduling.

4. Results

4.1. Methodology

The MILP modeling is done using the software XPRESS-MP release 2008A [34]. An Intel(R) Core(TM)2 Duo CPU @ 2.00 GHz and 1.00 GB of RAM was used for the resolution of the MILP model. For the sequential approach two computer programs SEQ.mos and CHP.mos were developed. *SEQ.mos* uses Eqs. (1)–(5) and Eq. (Crit. 1) to determine task scheduling (step 1 of sequential approach). Then Eqs. (33) and (34) are used to evaluate the utility requirements (step 2 of the sequential approach). Eq. (35) represents the steam and electricity demands of the manufacturing unit. On the basis of the utility requirements the computer program *CHP.mos* uses the Eqs. (6)–(32) and the Eq. (Crit. 2) to determine the operational planning of the CHP plant (step 3 of the sequential approach).

Table 3
Description of utility flow ratios.

Flow ratio	Equations	Description
Turbine Ratio	$\left(\frac{\sum_{t=1}^{T}\sum_{j\in TURB} TXHP_{t,j}}{\sum_{t=1}^{T}\sum_{j\in BOIL}\sum_{i\in FUEL} XHP_{t,j,i}-\sum_{t=1}^{T} DemHP_t}\right)\times 100$	Ratio of HP steam entering turbine to net steam available after fulfilling the HP steam demands.
Electricity Ratio	$\left(1-\frac{\sum_{t=1}^{T} ELP_t}{\sum_{t=1}^{T} DemEL_t}\right)\times 100$	The net percentage of electricity produced by the turbines of CHP plant.
HPRV Ratio	$\left(\frac{\sum_{t=1}^{T} LXHP_{t,j}}{\sum_{t=1}^{T}\sum_{j\in BOIL}\sum_{i\in FUEL} XHP_{t,j,i}-\sum_{t=1}^{T} DemHP_t}\right)\times 100$	Ratio of HP steam passing through high pressure relief valves to net steam available after fulfilling the HP steam demands.
LPRV Ratio	$\left(\frac{\sum_{t=1}^{T} LXMP_t}{\sum_{t=1}^{T} LXMP_t+\sum_{t=1}^{T}\sum_{j\in TURB} XLP_{t,j}}\right)\times 100$	Ratio of LP steam passing trough low pressure relief valve to the total LP steam generated to meet the low pressure demands.

In the integrated approach one computer program, *INTEG.mos*, is used to simultaneously carry out task scheduling and operational planning of the CHP plant by concurrently solving Eqs. (1)–(35) and Eq. (Crit. 2). The planning horizon of 80 hours is divided in to 10 cycles (8 hour duration each). The manufacturing unit must fulfill a certain demand of final products at the end of each cycle.

4.2. *Comparison criteria*

The two approaches will be judged on the following three criteria:

i. Energy costs:

The primary criterion for the comparison is the Eq. (Crit. 2) i.e. energy costs. To gauge the environmental effect, SO_x and GHG emissions are also compared.

ii. Utility flow ratios:

The whole objective of the integrated approach is to maximize the use of turbines and minimize the use of PRVs. Four flow ratios are therefore used to compare the two approaches (Table 3).

iii. Convergence history:

The important aspects in this regard are convergence time and the gap between the optimal solution and the bounded solution. The total iteration time for the sequential approach is calculated by combining the iteration times for the XPRESS application, *SEQ.mos* and *CHP.mos*. To judge against the integrated approach this combined iteration time is compared to the iteration time for *INTEG.mos*. As a rule, all the simulations, which had not completely converged after thirty minutes, were stopped, except for those whose gap was more than 10%. In these cases the simulations were allowed to run until they achieved a gap of less than 10%.

4.3. *Examples*

To compare the integrated and sequential approaches three different manufacturing units are considered. For the purpose of clarity, example 1 (multi-product flow shop) will be presented in detail while the results of other manufacturing units will be briefly summarized in the subsequent section. To further simplify the analysis, the same CHP plant parameters are considered for all three examples. The input parameters for each example, including the utility consumption matrix ($Cop_{v,k}$) and the CHP plant, are provided in the appendix III.

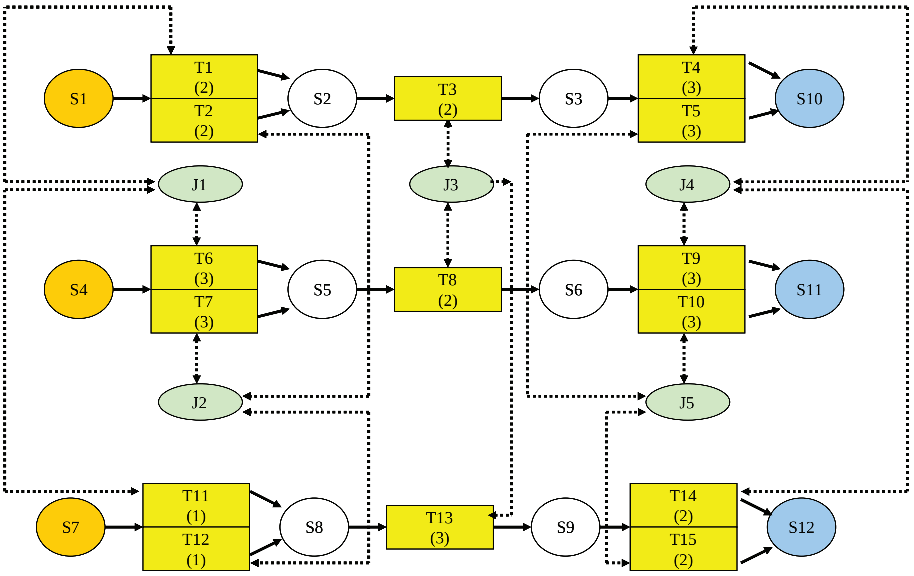

Fig. 7. RTN representation of example 1.

Table 4
Overall energy costs for example 1, 2 & 3.

Capacity		**50%**		**60%**		**80%**		**90%**		100%	
		Sequential	**Integrated**	**Sequential**	**Integrated**	**Sequential**	**Integrated**	**Sequential**	**Integrated**	**Sequential**	**Integrated**
Example 1	**Fuel Cost** (€)	40,750.3	29,422	45,690	35,985.7	56,281.9	47,696.4	61,432.6	55,942.4	67,823.6	61,064.6
	Electricity Cost (€)	4,536.56	2,201.74	5,453.7	2,268.84	7,793.19	3,392	8,579.78	2,759.84	8,940.47	3,585.07
	SO$_x$ Emission Cost (€)	242.281	244.945	292.491	235.237	359.834	299.944	420.924	427.55	455.937	467.267
	Total Cost (€)	45,529.1	31,868.7	51,436.2	38,489.8	64,434.9	51,388.4	70,433.3	59,129.8	77,220	65,116.9
	GHG Emissions (tons)	2,009.80	1,514.75	2,272.38	1,794.17	2,798.74	2,367.27	3,080.48	2,845.41	3,392.97	3,106.45
	SO$_x$ Emission (tons)	10.53	10.65	12.72	10.23	15.64	13.04	18.30	18.59	19.82	20.32
Example 2	**Fuel Cost** (€)	66,788.1	61,429.7	77,875	74,166.3	103,878	101,758	119,179	114,006	127,514	125,486
	Electricity Cost (€)	8,189.77	3,340.29	9,090.18	3,838.37	11,261.8	5,986.99	12,540.5	6,797.93	14,551.6	8,684.12
	SO$_x$ Emission Cost (€)	397.09	424.65	463.01	531.92	617.61	653.72	830.50	750.15	898.79	770.77
	Total Cost (€)	75,374.9	65,194.7	87,248.2	78,536.6	115,758.0	108,339.0	132,550.0	121,554.0	142,066.0	134,941.0
	GHG Emissions (tons)	3,293.99	3,083.74	3,840.80	3,740.59	5,123.27	5,063.01	5,988.76	5,688.53	6,416.89	6,211.41
	SO$_x$ Emission (tons)	17.26	18.46	20.13	23.13	26.85	28.42	36.11	32.62	39.08	33.51
Example 3	**Fuel Cost** (€)	52,450.8	29,592	55,940.2	38,776.3	70,070.2	54,749	77,284.4	63,616.8	84,085.3	72,260.5
	Electricity Cost (€)	4,021.5	1,096.94	6,529.7	1,181.21	9,480.86	2,152.73	11,361	2,509.3	12,560.3	2,697.25
	SO$_x$ Emission Cost (€)	372.49	196.338	352.96	283.413	416.6	346.621	459.494	471.539	521.64	505.741
	Total Cost (€)	56,844.8	30,885.3	62822.9	40240.9	79967.6	57248.4	89104.9	66597.7	97167.8	75463.5
	GHG Emissions (tons)	2,642.01	1,478.03	2,777.49	1,950.52	3,455.86	2,719.42	3,811.67	3,222.42	4,166.83	3,633.10
	SO$_x$ Emission (tons)	16.20	8.54	15.36	12.32	18.11	15.07	19.98	20.50	22.68	21.99

4.3.1. *Example 1*

The production recipe of the multi-product flow shop (Fig. 7) uses five different processing equipments to convert three raw materials S1, S4 & S7 into three finished products S10, S11 & S12. The maximum production capacity is established using Eqs. (1)–(5) and the criteria of production maximization.

$$C_{\mathrm{stock}} = \sum_{s \in \mathrm{products}} D_{s,t} \quad \forall t = 1, .., T \qquad \text{(Crit. 3)}$$

Based on this maximum production capacity, five scenarios are developed in which the manufacturing unit respectively operates at capacities of 50%, 60%, 80%, 90% and 100%. The sequential and integrated approaches are then compared based on energy costs, flow ratios and convergence history for each of these five scenarios.

The integrated approach leads to significant energy cost savings and reductions in emissions of SO$_x$ and GHG (Table 4). However, these cost savings decrease when the manufacturing unit operates

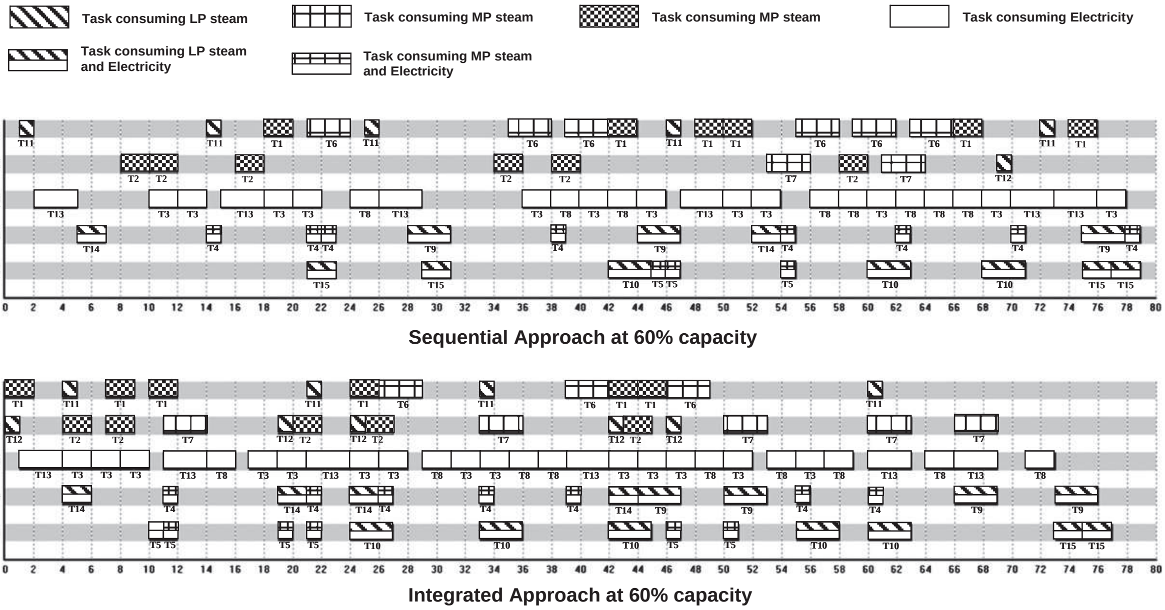

Fig. 8. Task scheduling of manufacturing unit operating at 60 % capacity.

Table 5
Utility flow ratios for example 1, 2 & 3.

Capacity		**50%**		**60%**		**80%**		**90%**		**100%**		Average	
		Seq.	**Integ.**	**Seq.**	**Integ.**	**Seq.**	**Integ.**	**Seq.**	**Integ.**	**Seq.**	**Integ.**	**Seq.**	**Integ.**
Example 1	**Turbine ratio (%)**	65.74	89.36	66.33	92.14	62.63	89.93	61.22	96.74	65.17	93.81	64.22	92.40
	Electricity ratio (%)	50.57	76.02	50.49	79.41	46.92	76.91	48.06	83.30	51.29	80.47	49.47	79.22
	HPRV ratio (%)	34.26	10.64	33.67	7.86	37.37	10.08	38.78	3.26	34.83	6.18	35.78	7.60
	LPRV ratio (%)	26.78	10.74	22.45	6.50	43.22	6.32	37.05	2.92	41.19	3.78	34.14	6.05
Example 2	**Turbine ratio (%)**	65.74	89.36	78.34	96.14	81.72	96.07	83.08	96.91	81.01	92.20	77.98	94.14
	Electricity ratio (%)	50.57	76.02	67.96	85.72	70.74	84.45	71.23	84.41	70.12	82.02	66.12	82.52
	HPRV ratio (%)	34.26	10.64	21.66	3.86	18.28	3.93	16.92	3.09	18.99	7.80	22.02	5.86
	LPRV ratio (%)	26.78	10.74	20.33	1.19	14.56	1.25	13.09	1.74	13.13	2.45	17.58	3.48
Example 3	**Turbine ratio (%)**	67.89	94.52	68.49	99.88	63.21	98.88	61.64	98.36	62.59	98.64	64.76	98.06
	Electricity ratio (%)	62.53	89.76	53.79	91.62	54.69	89.70	53.28	89.66	54.68	90.26	55.79	90.20
	HPRV ratio (%)	32.11	5.48	31.51	0.12	36.79	1.12	38.36	1.64	37.41	1.36	35.24	1.94
	LPRV ratio (%)	44.46	0.32	43.08	0.00	44.55	0.00	39.28	0.40	33.50	0.00	40.98	0.14

at or near its maximum (100%) capacity. This is due to the fact that, while operating near the peak capacity, the manufacturing unit has a comparatively lesser degree of freedom in shifting and rearranging the tasks. Hence, relatively smaller gains in energy cost and emission savings are achieved.

A task scheduling Gantt diagram at 60% capacity illustrates the difference between the sequential and integrated approaches (Fig. 8). It is clear that in the case of the integrated approach the tasks in the manufacturing unit are arranged in such a manner that their utility requirements are synchronized with the utility generation in the CHP plant. This not only minimizes the wastage of utilities but it also means that instead of using pressure reducing valves, steam turbines are used to meet the low and medium pressure steam demands. Table 5 demonstrates that the integrated approach maximizes the use of turbine operation and limits the use of pressure reducing valves leading to more onsite electricity generation and reduced dependence on external electricity suppliers.

In terms of convergence criteria the sequential approach is superior to the integrated approach (Table 6). The sequential approach is not only much faster, but it almost contains no convergence gap, the only exception being the manufacturing unit operating at 90% capacity where the gap was of less than 1%. On the other hand, the average convergence gap in the integrated approach turns out to be 7.98%. This might appear to be a drawback but it is important to note that, despite this convergence gap, the integrated approach leads to energy cost savings of between 15 and 30% and GHG emission reductions of between 7 and 24%.

4.3.2. Example 2

Fig. 9 shows the production recipe of example 2. The overall benefits (Table 4) in this case are less than those attained in example 1. The energy cost saving of 13% is achieved by the manufacturing unit operating at a 50% capacity while these savings reduce to 5% when the manufacturing unit operates at a 100% capacity. The reason for this diminished gain is also partly due to the slow convergence and gap between the solutions achieved and the best bounded solution. The convergence history (Table 6) shows that the convergence of example 2 is considerably slower than that of example 1. Even the sequential approach takes more time to converge and in certain cases complete convergence is not achieved. The average gap in the sequential approach simulations turns out to be 1.8 % while in the integrated approach it is 7.4%. For the scenarios in which the manufacturing unit operated at capacities of 80, 90 and 100% the gap is greater than 8%. In the case of 100% capacity the convergence is extremely slow and no solution is reached during the first 30 minutes. It can be inferred that if the simulations are allowed to run for a longer duration then this gap might reduce and subsequently a greater gain in overall energy savings may be achieved.

Table 5 reveals some interesting details about example 2. The average turbine ratio using the sequential approach was 68% in example 1 while it was a healthy 81% in example 2. This means that the structure of the manufacturing unit and the problem parameters in example 2 are such that there is less potential for overall energy cost savings. The analysis of the RTN diagram shows that

Table 6
Convergence history for example 1, 2 & 3.

Capacity		**50%**		**60%**		**80%**		**90%**		100%	
		Sequential	**Integrated**	**Sequential**	**Integrated**	**Sequential**	**Integrated**	**Sequential**	**Integrated**	**Sequential**	**Integrated**
Example 1	**Best Solution**	45,529.1	31,868.7	51,436.2	38,182.3	64,434.9	51,388.4	70,433.3	59,129.8	77,220.0	65,116.9
	Gap (%)	0.0	6.83	0.0	7.15	0.0	7.57	0.89	9.60	0.0	8.75
	Best Solution Time	2 min 48.6 s	22 min 23.5 s	20 min 26.8 s	30 min 4 s	5 min 55.9 s	22 min 8.9 s	25 min 8.0 s	20 min 47.3 s	30 min 30.5 s	8 hr 17 min
	Total Iteration Time	3 min 26.9 s	30 min 1 s	22 min 26.8 s	30 min 7.2 s	5 min 55.9 s	30 min 4.3 s	32 min 16.4 s	30 min 5.2 s	30 min 30.5 s	8 hr 33 min
Example 2	**Best Solution**	75,374.9	65,194.7	87,428.2	78,004.6	115,758	108,399	132,55	121,554	142,066	134,941
	Gap (%)	0.0	5.79	0.0	6.0	1.45	8.7	2.51	8.02	1.89	8.36
	Best Solution Time	18.7 s	14 min 4.2 s	38 min 22.2 s	27 min 5.1 s	25 min 12.1 s	4 min 42.6 s	55 min 43 s	9 min 40.5 s	2 hr 12 min	15 hr 14 min
	Total Iteration Time	42.5 s	30 min 7.1 s	49 min 12.8 s	30 min 2.8 s	1 hr 1 min	30 min 0.8 s	1 hr 3 min	8 hr 06 min	4 hr 38 min	24 hr
Example 3	**Best Solution**	56,844.8	30,885.3	62,822.9	40,240.9	70,967.6	57,248.4	89,104.9	66,597.7	97,167.8	75,463.5
	Gap (%)	1.93	6.32	0.0	7.88	0.0	6.78	0.0	7.38	0.84	6.12
	Best Solution Time	8 min 1.4 s	33 min 1.4 s	3 min 11.6	4 min 38.6 s	12 min 24.8 s	21 min 4.6 s	23 min 17.5 s	24 min 48.8 s	16 min 22.8 s	1 hr 8 min
	Total Iteration Time	30 min 43 s	35 min 2 s	3 min 26.1 s	30 min 16.8 s	14 min 16.6 s	30 min 37.6 s	32 min 09.7 s	30 min 2 s	37 min 31.3 s	4 hr 35 min

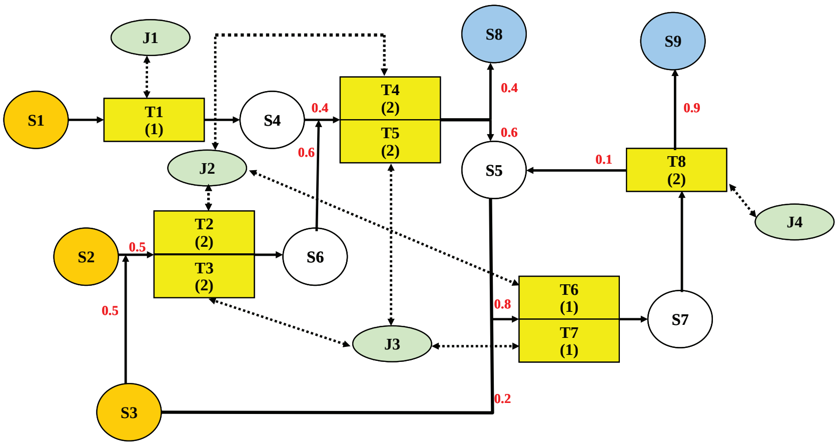

Fig. 9. RTN representation of example 2.

example 2 is more constrained with both fewer resources and tasks. This shows that the reductions in overall energy costs and in emissions are dependent on the production recipes and the processing equipment resources.

4.3.3. Example 3

Fig. 10 shows the production recipe of example 3, which has the greatest number of resources among all the examples considered. This provides the integrated approach with more latitude to synchronize the manufacturing unit and the utility system. As a result, greater savings in the overall energy costs, ranging from 22% to 45%, are obtained (Table 4). Similarly the GHG emission reductions between 12 and 44% are also achieved. The convergence in example 3 is faster than example 2 but a little slower than that in example 1 (Table 5). Complete convergence is achieved in all cases of the sequential approach while in the integrated approach the convergence gap is 6% on average.

4.4. Result analysis

On the basis of the above three examples it can be concluded that there are significant energy cost savings and emission reduction advantages in coupling the operational planning of the utility system with the task scheduling of manufacturing. Moreover, the use of the integrated approach enables an industrial unit to achieve higher productivity levels as it can handle scheduling regimes that would be unattainable using the sequential approach (as demonstrated in appendix I). Hence, rather than using the traditional sequential approach industrial units should adopt the integrated approach.

However, the use of the integrated approach evokes some interesting issues. Firstly, significant computation time may be required to resolve the integrated model. Even though this is a very restrictive constraint it is not critical because:

- This tool is used offline which can allow a response time of several hours.
- A “good” solution (that is to say, better than the sequential approach) may often be obtained with a reduced computational effort.

However, this computation time problem should not be overlooked, especially if the integrated approach is going to be applied to an industrial size problem or if it is integrated into a tool for decision support for which the time response must be much shorter (in order of minutes). In this context, several alternatives can be envisaged. For example, meta-heuristics (genetic algorithm, neighborhood methods) could be used to control the combinatorial aspect of the problem. Another alternative is to use the solution provided by the sequential approach (usually obtained within a shorter time) as the first solution of the integrated approach. This

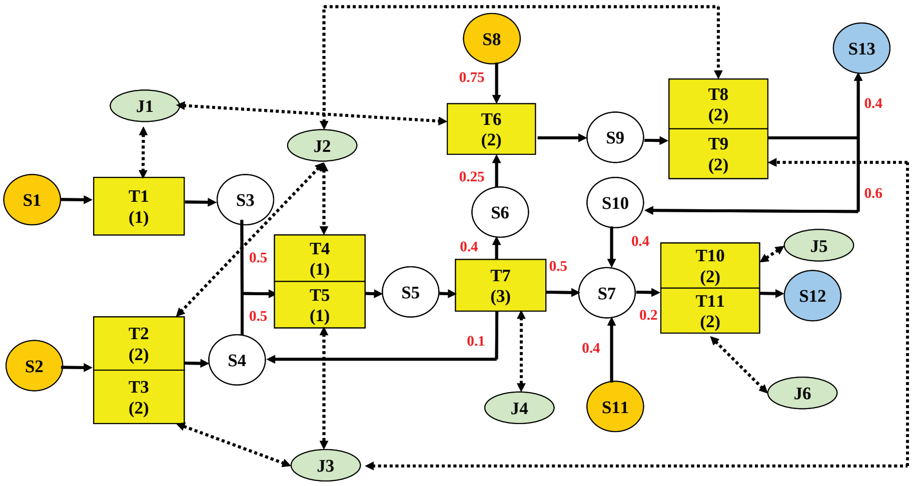

Fig. 10. RTN representation of example 3.

Table 7
Utility Consumption Matrix ($Cop_{v,k}$).

Tasks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
LP steam	0	0	0	0	0	0	0	0	4	4	3	3	0	2	2
MP Steam	0	0	0	4	4	3	3	0	0	0	0	0	0	0	0
HP Steam	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0
Electricity	0	0	0.2	0.1	0.1	0	0	0.2	0.1	0.1	0	0	0.2	0.1	0.1

will reduce the research space for the solver and will reduce the iteration time for the integrated approach. Moreover, distributed computing can also be used to reduce the computing time.

Secondly, the multi-objective function used in this study is composed of energy costs (fuel and electricity) and penalty costs for emissions of harmful gases. As a result, all the emphasis is placed on adapting the task scheduling of the manufacturing unit to meet the most cost efficient operational planning of the utility system. However, in the industry, the reliability of the production process is of overriding importance and normally a *reserve margin* is set in case of a delay or breakdown in the utility system. This reserve margin could be incorporated using a *weighted sum* of inventory levels (of raw materials, intermediate and finished products) and operational costs (fuel, electricity, penalty costs, etc.) of the utility system as the objective function. Moreover, by varying the weights of the coefficients, a number of task schedules can be developed, which include all the foreseeable scenarios such as the breakdown of machinery in the utility system.

Another possibility of including a reserve margin in the integrated approach is the use of multi-criteria optimization. This would present the management of an industrial unit with multiple solutions (based on the chosen criteria) and allow them to select the most beneficial solution.

Finally, for this study, the emission penalty costs were significantly underplayed. However, the multi-objective function (Eq. (Crit.2)) can be used to analyze and develop future scenarios when, and if, the proposed taxes on carbon emissions and other harmful gases come into effect. It should be emphasized that care must be taken while considering the associated emission penalty costs as they have a profound impact on the overall costs (as demonstrated in appendix II).

5. Conclusion

The energy issue is a crucial problem and will become increasingly important in the coming decades. Greater energy costs and progressively stringent environmental laws are forcing the industrial sector to streamline their energy consumption. CHP based onsite utility systems can make a useful contribution in this regard especially in the case of industrial units which have high energy needs. However, to maximize the potential of the CHP based onsite utility systems, it is imperative to manage the utilities better. Contrary to the traditional reasoning of placing the emphasis solely on production (manufacturing unit) and treating the utility system as a subsidiary unit, it is vital to develop an integrated approach which simultaneously carries out the task scheduling of manufacturing unit and the operational planning of utility system.

The results demonstrate that the integrated approach leads to better coordination between the manufacturing unit and site utility system, which in turn leads to significant reductions in energy costs and emissions of harmful gases. However, implementation of the integrated approach in a real industrial environment would depend upon two factors: (a) extensive use of computer aided tools and (b) enhanced cross functional communication between the management of respective manufacturing unit and utility system. The integrated approach would be difficult to implement in industrial units with rigid centralized organizational structures.

In the future, a continuous-time MILP model will be developed that will incorporate additional constraints such as equipment cleaning, variation of task duration with batch size and the use of different utilities during the successive phases of the same task (for example, a reaction that requires preheating at the start and cooling at the end). Inevitably, this will add to the complexity of the integrated model and probably aggravate the existing dilemma of problem resolution time. This could eventually require the development of an intermediary approach, which combines the advantages of both the faster resolution time of the sequential approach with the greater operational profitability offered by the integrated approach.

Acknowledgements

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Appendix I. – higher productivity potential of integrated approach

Consider a utility consumption matrix ($Cop_{v,k}$) and its corresponding energy costs demonstrated in Tables 7 and 8 respectively.

Table 8
Overall energy costs.

Capacity	Approach	Total Cost (€)	Fuel Cost (€)	Electricity Cost (€)	SO_x Cost (€)	GHG Emissions (tons)	SO_x Emissions (tons)
100 %	Sequential	not feasible	not feasible	not feasible	not feasible	not feasible	not feasible
	Integrated	128,068.7	116,457.0	10,898.0	713.7	5,763.0	31.0
90 %	Sequential	not feasible	not feasible	not feasible	not feasible	not feasible	not feasible
	Integrated	116,522.6	104,958.0	10,916.8	647.8	5,198.1	28.2
80 %	Sequential	116,210.5	96,450.5	19,095.9	664.1	4,839.4	28.9
	Integrated	102,416.5	91,850.7	9,998.4	567.4	4,549.4	24.7
60 %	Sequential	89,553.0	75,357.7	13,656.1	539.2	3,799.5	23.4
	Integrated	76,707.2	69,291.5	6,971.9	443.8	3,446.4	19.3
50 %	Sequential	75,759.0	63,206.9	12,136.3	415.8	3,153.8	18.1
	Integrated	63,222.5	57,356.3	5,525.2	341.0	2,828.8	14.8

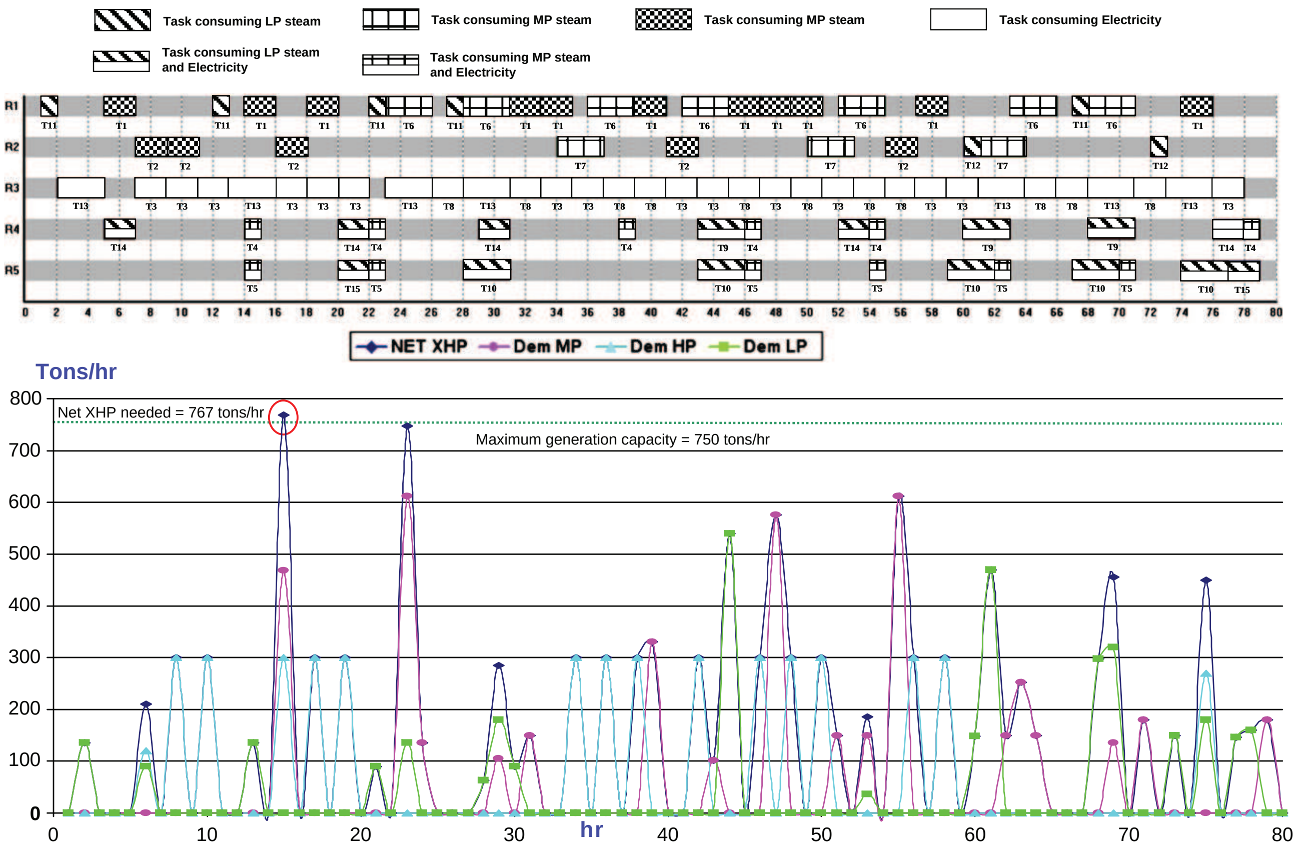

Fig. 11. Sequential approach task scheduling Gantt diagram and steam load curves of utility system.

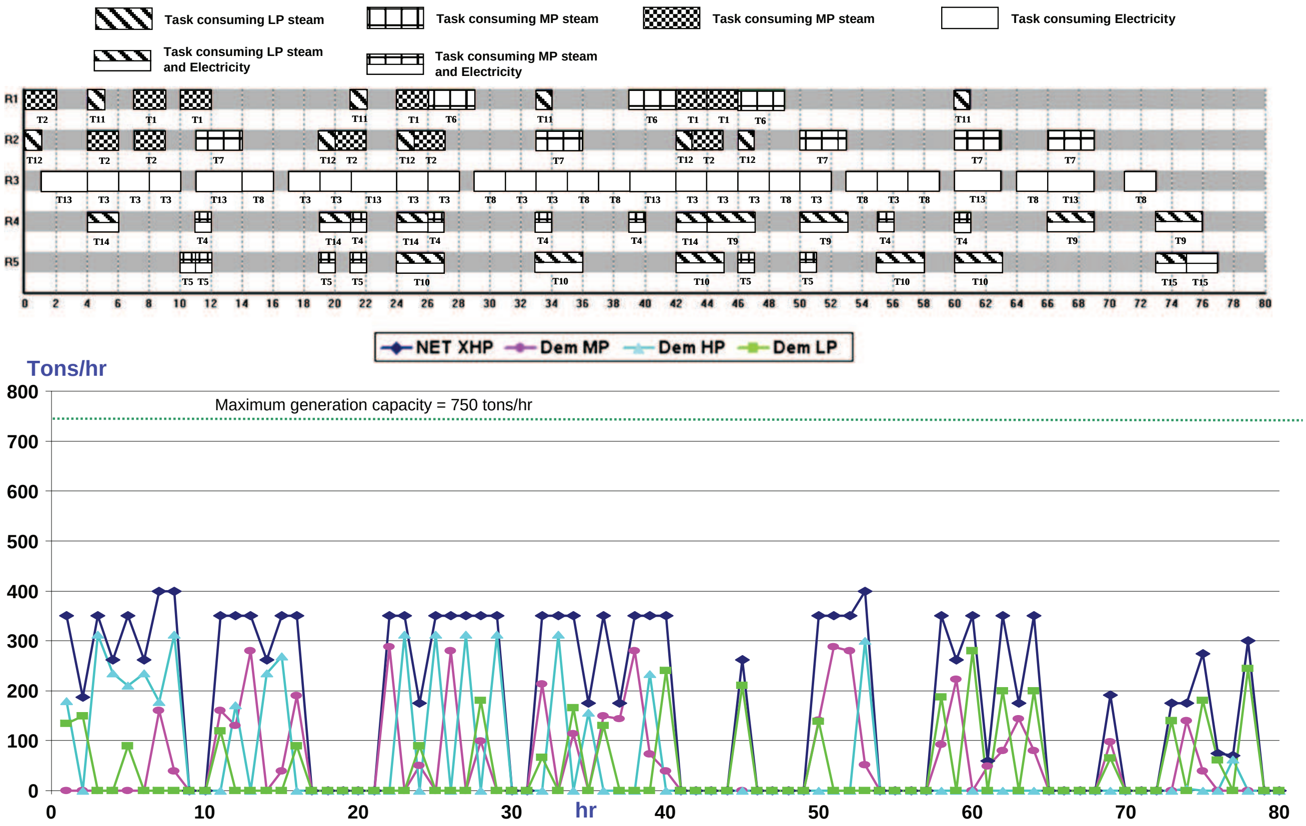

Fig. 12. Integrated approach task scheduling Gantt diagram and steam load curves of utility system.

Table 9
Incorporating full emission externality cost for example 3 functioning at 60% capacity.

Emission externality cost €/ton		Total Cost (€)	Fuel Cost (€)	Electricity Cost (€)	GHG Cost (€)	SO_x Cost (€)	GHG Emissions (tons)	SO_x Emissions (tons)
GHG	SO_x							
115.65	3640.54	293,795	36,015.5	14,935.1	206,834	36,011	1788.45	9.89
0	23	40,40.9	38,776.3	1,181.21	0	283,4	1968.52	12.32

Table 10
Utility consumption matrix ($Cop_{v,k}$) for example 1.

Tasks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
LP steam	0	0	0	0	0	0	0	0	2	2	1.5	1.5	0	1	1
MP Steam	0	0	0	2	2	1.5	1.5	0	0	0	0	0	0	0	0
HP Steam	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0
Electricity	0	0	0.1	.05	.05	0	0	.05	.05	.05	0	0	0.1	.05	.05

Table 11
Parameters for manufacturing unit example 1.

	$V_{k,j}^{min}$	$V_{k,j}^{max}$	
Unit 1	10	100	
Unit 2	10	80	
Unit 3	10	50	
Unit 4	10	80	
Unit 5	10	80	
	l_s	C_s^{max}	C_s^o
State 1	0	100,000	5,000
State 2	1	200	0
State 3	1	250	0
State 4	0	100,000	5,000
State 5	1	200	0
State 6	1	250	0
State 7	0	100,000	5,000
State 8	1	200	0
State 9	1	250	0
State 10	2	10,000	0
State 11	2	10,000	0
State 12	2	10,000	0
Maximum (100 %) production capacity	*Product A* = *State* 10	*Product B* = *State* 11	*Product C* = *State* 12
Cycle 1	0	0	50
Cycle 2	130	0	0
Cycle 3	170	0	50
Cycle 4	0	50	50
Cycle 5	50	0	0
Cycle 6	160	150	0
Cycle 7	170	0	20
Cycle 8	70	130	0
Cycle 9	50	130	0
Cycle 10	50	50	170

Table 13
Parameters for manufacturing unit example 2.

	$V_{k,j}^{min}$	$V_{k,j}^{max}$	
Unit 1	10	100	
Unit 2	10	80	
Unit 3	10	50	
Unit 4	10	100	
	l_s	C_s^{max}	C_s^o
State 1	0	10,000	5,000
State 2	0	10,000	5,000
State 3	0	10,000	5,000
State 4	1	100	5,000
State 5	1	200	0
State 6	1	150	0
State 7	1	100	0
State 8	2	10,000	0
State 9	2	10,000	0
Maximum (100 %) production capacity	*Product A* = *State* 8	*Product B* = *State* 9	
Cycle 1	0	0	
Cycle 2	0	233	
Cycle 3	0	0	
Cycle 4	0	133	
Cycle 5	0	0	
Cycle 6	0	258	
Cycle 7	258	258	
Cycle 8	258	258	
Cycle 9	258	258	
Cycle 10	258	158	

The Table 8 shows that integrated approach not only results in reduction in energy costs but it also leads to feasible solution for all five scenarios. On the other hand the sequential approach gives infeasible solutions in scenarios where manufacturing unit operates at 90% and 100% capacity.

For the scenario in which manufacturing unit operates at 90% capacity Figs. 11 and 12 presents the task scheduling Gantt diagrams and operational planning of utility system (depicted by steam load curves). The sequential approach calculates task scheduling without considering operational constraints of the CHP plant. As a result not only there are huge variations in the steam load curves but during period $t = 15$ the steam demands of the manufacturing unit exceed the generation capacity of the CHP plant. This resulted in sequential approach rendering infeasible solution. On the other hand in the integrated approach the tasks are shifted and rearranged in such a manner that the utility requirements never exceed the CHP plant capacity. From this an inference can be drawn that the integrated approach enables an industrial

Table 12
Utility consumption matrix ($Cop_{v,k}$) for example 2.

Tasks	1	2	3	4	5	6	7	8
LP steam	0	0	0	2	2	0	0	1
MP Steam	0	2	2	0	0	0	0	0
HP Steam	4	0	0	0	0	0	0	0
Electricity	0	0.1	0.1	0.1	0.1	0.1	0.1	0

Table 14
Utility consumption matrix ($Cop_{v,k}$) for example 3.

Tasks	1	2	3	4	5	6	7	8	9	10	11
LP steam	0	0	0	1	1	0	2	0	0	0	0
MP Steam	0	1.5	1.5	0	0	0	0	1	1	0	0
HP Steam	1	0	0	0	0	1	0	0	0	0	0
Electricity	0	0.1	0.1	0.1	0.1	0	0	0	0	0.1	0.1

unit to achieve higher productivity as it can handle scheduling regimes that would be unattainable using the sequential approach.

Appendix II – impact of emission externalities on overall problem

For this study emission costs constituted less than 1% of overall costs. This correlates with the current economic situation where no monetary punishments are associated with harmful gas emissions. However, multi-objective function (Crit. 2) can used to develop scenarios in which emission costs have a greater impact. Table 9 shows result of an additional simulation which was based on emission externality costs of El-Kordy et al. [35].

The emission costs become a dominant factor (83 % of overall costs). Even though fuel cost decrease by 7 % but electricity cost see a massive increase. This is expected as rather than minimizing energy cost associated with fuel and electricity purchase all the effort is spent in reducing the emissions of harmful gases. As a result GHG emissions are reduced by 9 % while those of SO_x are reduced by almost 20%.

The results also demonstrate that imposing high carbon tax and other emission penalty cost would nullify the use of CHP technology. Faced with steep emission penalties the industrial units would prefer to buy electricity from external source rather than producing it through cogeneration. This is an extreme example which was presented just to demonstrate impact of emission externalities. From this it can be concluded that incorporating emission penalty cost have huge influence on the problem parameters and their numerical values should be selected carefully.

Table 15
Parameters for manufacturing unit example 3.

	$V_{k,j}^{\min}$	$V_{k,j}^{\max}$	
Unit 1	10	100	
Unit 2	10	80	
Unit 3	10	50	
Unit 4	10	70	
Unit 5	10	100	
Unit 6	10	100	
	I_s	$C_s^{\max}$	C_s^o
State 1	0	10,000	5,000
State 2	0	10,000	5,000
State 3	1	100	5,000
State 4	1	100	5,000
State 5	1	300	0
State 6	1	150	0
State 7	1	150	0
State 8	0	10,000	5,000
State 9	1	150	0
State 10	1	150	0
State 11	0	10,000	5,000
State 12	2	10,000	0
State 13	2	10,000	0
Maximum (100 %) production capacity	*Product A* = *State* 12	*Product B* = *State* 13	
Cycle 1	0	0	
Cycle 2	100	0	
Cycle 3	33	0	
Cycle 4	133	132	
Cycle 5	133	0	
Cycle 6	133	64	
Cycle 7	133	78	
Cycle 8	133	108	
Cycle 9	0	40	
Cycle 10	0	112	

Table 16
Operating characteristics for the CHP plant.

Description	Fuel 1	Fuel 2
cc	23	16.70
$cpt_{i,j}$	3,000	10,000
ORF_{ij0}	3,000	3,000
ghg	2.466	1.858
SO_x	0.012925	0.02585
Cf	50	30
ssf (10% *of cpt*)	300	1,000
	Boiler 1	**Boiler 2**
$H1_{ji(fuel1)}$	0.80	0.80
$\eta 2_{ji(fuel1)}$	0.77	0.77
$\eta 3_{ji(fuel1)}$	0.70	0.70
$\eta 4_{ji(fuel1)}$	0.47	0.47
$\eta 1_{ji(fuel2)}$	0.65	0.65
$\eta 2_{ji(fuel2)}$	0.62	0.62
$\eta 3_{ji(fuel2)}$	0.55	0.55
$\eta 4_{ji(fuel2)}$	0.32	0.32
$XHPmax_j$	350	400
$XHPmin_j$	60	70
$SIdem_{ji(fuel1)}$	1.734	3.509
$SIdem_{ji(fuel2)}$	2.024	4.093
a_{ij}	0.10	0.10
b_{ij}	0.002	0.003
h_{fw}	0.56677	0.56677
	Turbine 1	**Turbine 2**
$TXHPmax_j$	500	500
$TXHPmin_j$	0	0
η_j	0.80	0.80
h_b	3.06677	3.06677
h_m	2.95509	2.95509
h_l	2.83875	2.83875
h_e	2.75268	2.75268
	Parameters	
COSTSOx	23.0	
COSTGHG	0.0	
COSTEL	80	

Appendix III – input data for the manufacturing unit and CHP plant

Example 1 (Tables 10 and 11)
Example 2 (Tables 12 and 13)
Example 3 (Tables 14 and 15)
CHP plant (Table 16)

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