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To cite this version:

Beatrice Marchi, Simone Zanoni, Lucio Zavanella. An Integrated Supply Chain Model with Excess Heat Recovery. IFIP International Conference on Advances in Production Management Systems (APMS), Sep 2017, Hamburg, Germany. pp.479-487, 10.1007/978-3-319-66926-7_55 . hal-01707280

HAL Id: hal-01707280
https://hal.inria.fr/hal-01707280

Submitted on 12 Feb 2018

An Integrated Supply Chain model with Excess Heat Recovery

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Abstract. Energy efficiency is gaining increasingly attention from industries and from several other stakeholders since energy costs cover a significant share of the industrial total cost for manufacturing companies. The improvement of the performances and the consequent reduction of energy consumption lead to multiple extra benefits in addition to cost savings, for instance improved competitiveness, profitability and quality. For that reason, energy efficiency should be considered as a strategic advantage instead of a marginal issue. The relevance of this issue is particularly significant in energy intensive processes such as the metal industry (e.g. steel and aluminium producers), where usually high temperature processes present a remarkable opportunity to save energy through the excess heat recovery. The aim of the present work is to study a single-vendor single-buyer integrated production-inventory system with the opportunity to recover energy from the excess heat at the vendor production site. The chance to incur in larger savings thanks to a wider integrated network of heat exchanges across various actors along the supply chain (integrated heat recovery) is analysed.

Keywords: Supply chain, Joint Economic Lot Sizing, Heat recovery, Energy efficiency

1 Introduction

The manufacturing sector is responsible for the majority of the energy consumed in industry which covers about 30% of the final energy consumption [1]. To reduce greenhouse gas emission and to send significant signals to the market, in 2012, the European Commission set a target of a 20% increase by 2020 of the energy efficiency compared with amount used in 2005. Recent studies [2, 3] claimed that making sustainable use of energy resources is becoming more critical for industrialized economies not only for the stringent targets imposed, but also for the geographic concentration and the huge prices of fossil fuels, and for the increasing customers' aware-

adfa, p. 1, 2011.

ness. Improved energy efficiency represents one of the most remarkable way for industries to reduce energy costs and to allow additional multiple benefits for the business such as enhanced productivity and competitiveness, reduced costs for environmental compliance, O&M and waste disposal and extended equipment lifetime [4]. These costs represent a relevant concern for companies, especially for energy-intensive processes (e.g. steel and aluminium industries) mainly because of the growing use and the high prices of fossil fuels. Since a noteworthy amount of wasted thermal energy is generated by these production processes, heat recovery presents a huge potential in the improvement of the energy efficiency [5]. Excess heat can be used by the same company for core processes or auxiliary services or transferred to other users with a demand for heat. Moreover, excess heat can also be converted into electricity through different technologies. Among these several technologies, the one that presents the best conversion efficiency is the organic Rankine cycle (ORC). However, to identify the real potential of the energy recovery it is important to undertake the implementation of other energy efficiency measures [6]: i.e. production planning, investment in energy-efficient equipment and recycling of energy in the industrial production process. In addition, since the coordination among different companies of the supply chain lead to different production planning, supply chain management can affect the effect of heat recovery. The coordination among different members of the supply chain generates positive impacts on the performance. A joint economic lot size (JELS) model with variable production rate was presented in [7]; while [8] proposes an analytical model representing a two-stage production system introducing the energy implications. However, these works do not consider the opportunity represented by heat recovery. Excess heat and controllable production rates were considered in [9] but in this study a two-stage production system was analysed while not the integrated decision-making among different actors of the supply chain, and the focus is on the only ORC technology. Hence, the aim of the present work is to model a single-vendor single-buyer integrated production-inventory system through a JELS model with the opportunity to recover energy from the excess heat through the investment in additional equipment. The chance to export the energy obtained from the heat recovery to other companies along the supply chain is also considered to represent the opportunity to incur in larger savings thanks to the wider integrated network. The remainder of the paper is organized as follows: Section 2 introduces the notations, assumptions and the analytical models development for the considered scenarios, Section 3 presents the solution of the models, Section 4 provides a numerical example to illustrate the behavior of the proposed models and, in conclusion, Section 5 summarizes the main findings and provides suggestions for future research.

2 Model development

2.1 Notation

α	[kW]	Constant of the power required by the vendor’s production process
A	[€/order]	Order cost

β	[kW/unit]	Coefficient for the contribution of the power required by the vendor's production process function of *P*
c_{HR}	[€/kWh]	Levelized cost of electricity for heat recovery equipment
δ	[kW/unit]	Coefficient that links the variable energy consumption contribution to the lot size at the buyer's site
D	[unit/h]	Demand rate
ε	[kW]	Constant of the energy required at the buyer's site
e_j	[€/kWh]	Cost of energy for actor j
$\dot{EC}_B$	[kW]	Power required by the production process at the buyer's site
$\dot{EC}_V$	[kW]	Power required by the production process at the vendor's site
η_{HR}	[%]	Conversion efficiency of the heat recovery technology
h_B	[€/unit·h]	Buyer's holding cost
h_V	[€/unit·h]	Vendor's holding cost
$\dot{HR}_B$	[kW]	Recovered heat at the buyer side
$\dot{HR}_V$	[kW]	Recovered heat at the vendor side
$\dot{HR}$	[kW]	Flow rate of waste heat recovered through the technology considered
n	[shipments]	Number of shipments
P_{min}	[unit/h]	Minimum value for the production rate
P	[unit/h]	Vendor's production rate
P_{max}	[unit/h]	Maximum value for the production rate
Q	[unit]	Lot size
S	[€/setup]	Setup cost
TC_B	[€/h]	Total annual cost of the buyer
TC_V	[€/h]	Total annual cost of the vendor
TC_S	[€/h]	Total annual cost of the supply chain
ω	[%]	Percentage of the required for the production process that is sent in input of the heat recovery technology as waste

2.2 Problem description and assumptions

This work analyses the coordination of a single-vendor single-buyer supply chain. The vendor manufactures a lot of size *nQ* at a set production rate *P* with a single setup which is delivered to the buyer in *n* shipments of equal-sized lots of *Q* units. The vendor incurs setup cost at the beginning of each production cycle, production costs continuously during production and revenues from selling the lot to the buyer at every shipment. In addition, it is assumed that the vendor must invest a capital amount in the equipment to allow the recovery of wasted heat. For the buyer, ordering and purchasing costs occur each time a shipment is made, while the continuous demand leads to continuous revenues over the entire cycle. As an extension of the traditional inventory theory, in this paper the two-stage supply chain is extended by introducing energy requirements and the opportunity to convert recovered waste heat into electricity.

The following section develops formal models to study the problem described above and considers different scenarios with regard coordination and heat recovery opportunity:

- Decentralized scenario without heat recovery (D.0) and with heat recovery at the vendor site (D.1)
- Centralized scenario without heat recovery (C.0) and with integrated heat recovery (C.1)

In addition to the properties already described, the following assumptions are made:

1. The inventory system involves a single item with an infinite planning horizon and shortages are not allowed
2. Production/purchasing costs and revenues are not differential
3. The demand rate (D) is constant
4. The vendor's production rate is limited to the interval [P_{min}, P_{max}], but it is always greater than the demand rate. As in [9], a 'rigid case' is considered: i.e. due to technological reasons, the production rates can be varied only before the start of the production
5. Cost of generating electricity from the heat recovery technology is defined by the levelized cost of electricity (LCOE) and includes the initial investment, operation and maintenance costs, cost of fuel and other accessories costs [10]
6. It is also assumed that the waste heat in input of the heat recovery system is proportional to the power required to run the production [9], $\dot{Q}^{in} = \omega \cdot E\dot{C}_V$.

2.3 Energy model

Several alternative technologies exist for the recovery of industrial excess heat [6], such as thermoelectric generator, Organic Rankine cycle (ORC), phase change material engine system and so on. All the technologies are characterized by a specific conversion efficiency, η_{HR}, depending on different factors (e.g. temperature of the heat source). According to [11, 12], the power requested for the production process consists of two contributions: one component is fixed and defined through a constant which usually comes from the equipment features required to support the process; while, the other is function of the current production rate, since, it depends on the physics of the process and on the quantity of product to be processed. The power request formulation is the same for both the actors but it is defined by different parameters.

$$E\dot{C}_V = \alpha + \beta n Q \tag{1}$$

$$E\dot{C}_B = \varepsilon + \delta Q \tag{2}$$

2.4 Economic models

Decentralized scenarios (D). In the decentralized scenarios, the vendor and the buyer take decisions separately to minimize their own total cost. The buyer should decide the size of the order quantity that minimizes the sum of order costs, inventory cost and energy cost. Thus, the buyer total cost TC_B is given by:

$$TC_B(Q) = A\frac{D}{Q} + h_B\frac{Q}{2} + e_B E\dot{C}_B \tag{3}$$

In the first scenario D.0, no waste heat recovery ($\dot{H}R = 0$) is considered, thus, the vendor does not incur into the additional cost of generating electricity from the recovery technology. Consequently, the vendor's total cost TC_V consists of the setup cost, inventory cost and energy cost; while the decision variables are identified by number of shipments, *n*, and the production rate, *P*.

$$TC_V(n,P) = S\frac{D}{nQ} + h_V\frac{Q}{2}\left[\frac{D}{P}(2-n) + n - 1\right] + e_V\dot{E}C_V\frac{D}{P} \tag{4}$$

In scenario D.1, the waste heat recovery is admitted at the vendor side. Hence, the annual total cost of the buyer remains unchanged (Eq. (3)) while the one of the vendor becomes:

$$TC_V(n,P) = S\frac{D}{nQ} + h_V\frac{Q}{2}\left[\frac{D}{P}(2-n) + n - 1\right] + \left[e_V\left(\dot{E}C_V - \dot{H}R_V\right) + c_{HR}\dot{H}R\right]\frac{D}{P} \tag{5}$$

where the heat recovery is given by the conversion efficiency and the amount of heat flow while the real recovery at the vendor site is given by the minimum between the power required for the production and the power recovered through the specific technology considered:

$$\dot{H}R = \eta_{HR} \cdot \omega \cdot \dot{E}C_V \tag{6}$$

$$\dot{H}R_V = min\{\dot{E}C_V; \dot{H}R\} \tag{7}$$

Centralized scenarios (C). In the centralized scenarios, the different actors cooperate in the decision-making process, to minimize the total cost of the supply chain reaching the global optimum instead of multiple local optimums. Also under coordinated decision two scenarios have been considered: in the first (C.0), no waste heat recovery is allowed; while, in the second (C.2), the case of integrated heat recovery is studied. The supply chain's annual total cost, TC_S, without heat recovery is given by the sum of eq.s (3) and (4):

$$TC_S(Q,n,P) = \left(A + \frac{S}{n}\right)\frac{D}{Q} + \frac{Q}{2}\left\{h_V\left[\frac{D}{P}(2-n) + n - 1\right] + h_B\right\} + e_B\dot{E}C_B + e_V\dot{E}C_V\frac{D}{P} \tag{8}$$

If integrated heat recovery is considered, the buyer incurs in extra-savings ($e_B\dot{H}R_B\frac{D}{nQ}$) due to the lower energy purchased from the grid. While, the vendor presents the same annual total cost as in scenario D.1 (Eq. (5)). Hence TC_S becomes:

$$\begin{aligned} TC_S(Q,n,P) = {} & \left(A + \frac{S}{n}\right)\frac{D}{Q} + \frac{Q}{2}\left\{h_V\left[\frac{D}{P}(2-n) + n - 1\right] + h_B\right\} + e_B\left(\dot{E}C_B - \frac{\dot{H}R_B}{n}\right) \\ & + \left[e_V\left(\dot{E}C_V - \dot{H}R_V\right) + c_{HR}\dot{H}R\right]\frac{D}{P} \end{aligned} \tag{9}$$

where the heat recovery transferred to the buyer, $\dot{H}R_B$, is given by the minimum between the energy required at the buyer's side and the energy recovered by the waste heat still not used by the vendor:

$$\dot{H}R_B = min\{\dot{E}C_B; \left(\dot{H}R - \dot{H}R_V\right)\} \tag{10}$$

3 Models solution

In the decentralized scenarios, the total cost of the buyer in the decentralized setting is the same with and without heat recovery. From the analysis of the objective function of the buyer, eq. (3), it is possible to demonstrate its convexity in *Q* and thus an optimal value for the lot size can be deducted:

$$Q^* = \sqrt{\frac{2AD}{h_B + 2e_B\varepsilon}} \tag{11}$$

For what concern the vendor, the objective functions, eq.s (4) and (5), present a convexity in *n* for given value of *P* and the optimal number of shipments is given by eq. (12) and (13) respectively for scenario D.0 and D.1.

$$n^*_{D.0} = \sqrt{\frac{2SD}{Q^2\left[h_V\left(1-\frac{D}{P}\right) + 2e_V\beta\frac{D}{P}\right]}} \tag{12}$$

$$n^*_{D.1} = \sqrt{\frac{2SD}{Q^2\left\{h_V\left(1-\frac{D}{P}\right) + 2[e_V(1 - min\{1;\eta_{HR}\omega\}) + c_{HR}\eta_{HR}\omega]\beta\frac{D}{P}\right\}}} \tag{13}$$

Since the number of shipments should be an integer, the optimal value $\tilde{n}^*$ is obtained comparing the total cost of the vendor rounding up and down the result of eq.s (12) and (13). Substituting $\tilde{n}^*$in eq.s (4) and (5), it is possible to study the convexity of the function in *P*. However, the obtained derivatives are quite complex and since the production rate should assumed an integer value between the two limits, [*P*$_{min}$, *P*$_{max}$], it is possible to use the following algorithm to find the optimal value of *P*.

Step 1 Set $Q = Q^*, n = \tilde{n}^*, P = P_{min}$ and $TC_V(\tilde{n}^*, P_{min}) = 0$.
Step 2 Calculate $TC_V(\tilde{n}^*, P)$ from eq.s (4) and (5).
Step 3 If $TC_V(\tilde{n}^*, P) > TC_V(\tilde{n}^*, P-1)$ then $P^* = P - 1$ otherwise set $P = P + 1$ and repeat step 2, in the range from *Pmin* to *Pmax*.

In the centralized scenarios, to find the optimal solutions, it is necessary to study the objective functions defined in eq.s (8) and (9) for scenario C.0 and C.1. Analysing the derivatives, it is possible to observe the convexity in Q of both the equations and the optimal values for the lot size of C.0 and C.1 are defined by eq.s (14) and (15) respectively.

$$Q^*_{C.0} = \sqrt{\frac{2\left(A+\frac{S}{n}\right)D}{h_V\left[\frac{D}{P}(2-n)+n-1\right] + h_B + 2e_B\delta + 2e_V\beta n\frac{D}{P}}} \tag{14}$$

$$Q^*_{C.1} = \\ = \sqrt{\frac{2\left(A+\frac{S}{n}\right)D}{h_V\left[\frac{D}{P}(2-n)+n-1\right] + h_B + 2e_B\left[\delta - \min\left\{\delta;\beta\left(\eta_{HR}\omega - \min\left\{1;\eta_{HR}\omega\right\}\right)\right\}\right] + 2\beta n\frac{D}{P}\left[e_V\left(1-\min\left\{1;\eta_{HR}\omega\right\}\right) + c_{HR}\eta_{HR}\omega\right]}} \tag{15}$$

Substituting Q^*in eq.s (4) and (5), it is possible to study the convexity of the function in *n* and *P*. However, the obtained derivatives are quite complex, hence, it is possible to use the following algorithm.

Step 1 Set $Q = Q^*, n = 1, P = P_{min}$ and $TC_S(Q^*, n, P_{min}) = 0$.
Step 2 Calculate $TC_S(Q^*, n, P)$.

Step 3 If $TC_S(Q^*, n, P) > TC_S(Q^*, n, P-1)$ then $P^* = P - 1$ otherwise set $P = P + 1$ and repeat step 2, in the range from *Pmin* to *Pmax*.
Step 4 Set $n = n + 1$ and repeat step 2 and 3.
Step 5 If $TC_S(Q^*, n, P^*) > TC_S(Q^*, n-1, P^*)$ then $n^* = n - 1$ otherwise go to step 4.

4 Numerical analysis

In the present section, a simple numerical example is presented to analyse the behavior of the model proposed. The data used for the analyses are presented in Table 1.

Table 1. Parameters used for the numerical analysis

α	10 kW	D	1000 unit/h	c_{ORC}	0.05 €/kWh
β	2 kW/unit	P_{min}	1000 unit/h	e_B	0.2 €/kWh
δ	0.5 kW/unit	P_{max}	2000 unit/h	e_V	0.15 €/kWh
ε	25 kW	S	400 €/setup	h_B	1.5 €/unit·h
η_{HR}	25%	A	100 €/order	h_V	3 €/unit·h
ω	80 %				

The results in Table 2 show that the lot size is reduced through the centralization and also shifting from scenario C.0 to C.1; while, in decentralized scenarios, the lot size is the same since it does not depend on the presence or absence of heat recovery initiatives. Conversely, the integrated scenario with heat recovery presents an increased production lot size (*nQ*); in this way, it is possible to incur in greater benefits.

Table 2. Results of the numerical example proposed

	D.0	**D.1**	**C.0**	**C.1**
Q [unit]	131.88	131.88	200.40	206.46
n [shipment]	9	9	5	6
P [unit/h]	1000	1000	1000	1000
TC_V *[€/h]*	€ 892.40	€ 844.72	€ 1,020.16	€ 955.97
TC_B *[€/h]*	€875.38	€875.38	€650.30	€664.85
TC_S *[€/h]*	€1,767.78	€1,720.10	€1,670.46	€1,620.82

The impact of the heat recovery in the reduction of the supply chain total cost is enhanced by the centralization of the joint decision-making: -2.97% shifting from scenario C.0 to C.1 against -2.70% from D.0 to D.1. At the same time, also the centralization allows greater reduction of the total cost if the excess heat recovery is allowed: -5.51% without recovery against -5.77% with recovery. In Fig. 1 the share of the cost components on the total cost of the supply chain is shown to observe the different impacts in the scenarios considered.

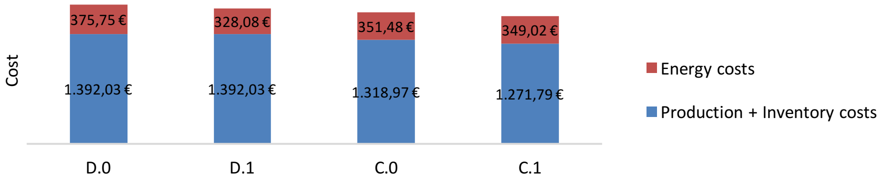

Fig. 1. Impact of the different costs components on the total supply chain cost

5 Conclusions

In the industrial sector, especially for energy intensive processes such as the metal industry, the recovery of the excess heat represents a great opportunity to increase the energy efficiency and thus to incur in relevant costs savings. The aim of the present work is to propose a model for studying a single-vendor single-buyer integrated production-inventory system with the opportunity to recover energy from the excess heat. The numerical example proposed shows that the centralization enhances the benefits introduced with the heat recovery and, at the same time, the presence of the recovery technology allows to increase the cost reduction obtained through the integrated decision-making. Future research could study more in details the behavior of the different heat recovery technologies, for example considering a conversion efficiency that depends on the power at which the technology works. Additional analysis should investigate the effect of considering a variable production rate at the vendor side which may lead to a trade-off between production-inventory costs and energy costs. Other extensions can be represented by the analysis of financial sharing and profit sharing mechanisms to make the centralization advantageous for both the supply chain members and by the integration of the thermal energy flow from the vendor to the buyer.

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