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The Relative Exergy Destroyed: A New Tool for Process Design and Control *

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Abstract— **Due to increasing energy demands and strict environmental regulations, the eco-efficiency of all industrial processes has become vitally important. Control system structure determination is a vitally important activity in process control and a poorly structured control strategy can lose a lot of energy in the process/plant. To save this energy, engineers need to find a way to integrate control loop configuration and measurements of eco-efficiency. In this paper, we present the relative exergy destroyed array (REDA), a new tool to measure the relative eco-efficiency of a process. Although based on steady state information, REDA still provides valuable information by comparing the eco-efficiencies of a process with several process control structures. The results obtained from the REDA are interpreted and explained with the help of two case studies. REDA can help guide the process designer to find a quick optimal control design with low operating cost/eco-efficiency.**

I. INTRODUCTION

Process control is a complex task divided into five main sub tasks, namely process design, control system structure selection, controller algorithm configuration, controller tuning and control hardware selection. Process design is the design of the process/plant that can be controlled easily. It is the first step in this complex task. Control system structure selection deals with control loop configuration or control pair selection. Controller algorithm configuration decides the type of controller e.g. P, PI, PID or MPC. The next sub task deals with tuning of controllers, which determines the tuning constants. The last part involves the selection of control hardware e.g. control valves, sensors and final control elements [1-2].

Control system structure selection is the second sub task in the process control task after process design, based on the type of control used for the process/plant. The process/plant can be either controlled by a centralized multi-input multi-output (MIMO) controller or by a set of single-input single-output (SISO) controllers also called decentralized controllers. Decentralized control systems are more common in industry and have more attractive advantages: i) simple algorithms; ii) easy to understand; iii) hardware simplicity and iv) design simplicity [2-3].

Control system structure selection for a decentralized control system focuses on deciding the best control scheme for pairing manipulated (MV) and controlled variables (CV). Control system structure selection is vital because a poor control structure will result in poor performance. To develop an effective control structure, selecting the best control configuration is important. For selecting the best control configuration, there are several common techniques in use such as the relative gain array (RGA), the Niederlinski index (NI), singular value decomposition (SVD), the condition number (CN), and Morari's resiliency index (MRI) [4-5]. These techniques only consider controllability and would not provide any information about eco-efficiency about the different control configurations.

In this modern age, control loop configuration cannot only focus on control loop analysis and consideration of the quality of control, but must also include energy usage, energy cost and environment impact. Thermodynamic properties like exergy have the potential to be used to improve the energy usage, decrease energy cost and environment impact. The concept of exergy unequivocally indicates what is wasted in terms of energy. More details on exergy are given by Szargut et al. [6]. The concept of exergy improves the energy usage and cost by providing a means of finding inefficient parts of a process/plant [6-9]. Exergy can also play an important role in controlling environmental impacts by reducing exergy losses and by the efficient use of exergy [10-13]. Eco-efficiency is achieved through the pursuit of three objectives: improving energy usage, lowering energy cost and reducing environment impact.

Exergy also has the potential to be used for the development of process control structures to integrate control loop configuration and eco-efficiency. A basic framework for the development of a dynamic exergy balance for process control evaluation has been proposed by Luyben et al. [1]. The Relative Exergy Array (REA) was developed based on analyzing the exergy interactions for the control configuration within the process design [14-15]. But REA measures the eco-efficiency only within the scope of the control loops studied. A new measure of eco-efficiency, exergy eco-efficiency factor (EEF), has also been proposed for the eco-efficiency analysis of the whole unit/process or even plant [16]. Some research has also been done on process control effects on entropy production [17-18].

The EEF integrates control loop configuration and eco-efficiency for the whole process. For a general MIMO process, a certain amount of exergy consumption/generation is needed to change one CV by using one MV. The EEF is

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designed to measure this amount of exergy for different control pairings. The control pairing which needs the least exergy to fulfill its control targets will be the most eco-efficient control pairing. The EEF helps engineers to select the best control configuration for eco-efficiency. This measure only considers the steady-state situation and ignores the exergy interaction. More details on the EEF are given by Munir et al. [16].

The relative exergy eco-efficiency factor array (REEFA) for an n x n MIMO process is defined analogously to RGA. The REEFA is an array of EEFs for all possible pairing combinations of a MIMO process. The combination (product) of REEFA and RGA helps to develop a new tool called Relative exergy destroyed array (REDA).

In this paper, the new, relative exergy destroyed array (REDA) tool is proposed to measure the relative eco-efficiency of a MIMO process for different combinations of control structures. The REDA compares the eco-efficiency of a process under different control structures including the exergy interaction.

This manuscript is organized as follows. After this general introduction, the concepts of eco-efficiency, EEF and RGA are explained, the REDA is proposed and guidelines for interpreting its results are presented and explained. Then, the proposed method is implemented for simulation examples. Finally, the results are discussed and conclusions are made in the summary.

II. ECO-EFFICIENCY, EXERGY ECO-EFFICIENCY FACTOR AND RELATIVE GAIN ARRAY

A. *Eco-efficiency*

Eco-efficiency is a strategy of doing more with less. Eco-efficiency is achieved through the pursuit of three main tasks: Optimized use of resources; reduced environmental impacts and increases in product/service value. It reduces material and energy intensity of products and increases product durability which results in cost saving and sustainability. Eco-efficiency also optimizes the use of materials/resources; minimizes waste and offers remanufacturing service [19].

As an eco-efficient process minimizes waste emissions, cost saving and sustainability, therefore it is ecologically friendly and economically viable. Ecological friendly means the process has less consumption of energy or destruction of exergy.

When applying the concept of eco-efficiency to control loop configuration, we developed a method which can help engineers select the manipulated variables which achieve the best products with the lowest energy cost. To achieve this aim, the EEF was developed.

B. *Exergy Eco-efficiency factor （EEF）*

The concept of EEF is based on exergy. The details of exergy, its calculations and its different components are explained by [20-21]. Exergetic efficiency, η, is defined as the ratio of the exergy going out to the exergy going into a process [6],

$$\eta = B_{Out} / B_{In} \qquad (1)$$

where η = Exergetic efficiency, B_{Out} = Total exergy going out of a process and B_{In} = Total exergy coming in to a process.

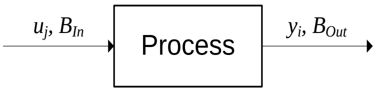

Figure 1: Exergy flows for a general process

The ratio can be used to measure the exergy efficiency of a process which is equivalent to eco-efficiency. A general process for exergetic efficiency calculation is shown Figure 1. The definition of total exergy and detailed exergy calculation procedures using the simulator software VMGSim can be found in [21-22].

Equation (2) includes the exergy efficiency for the whole process; however it does not provide any information about how the control loop configuration affects this exergy efficiency. A new measure, EEF, which connects the control loop configuration to the eco-efficiency, has been developed [16]. The EEF for a control pair (u_j, y_i), is defined as,

$$\tau_{ij} = (\Delta B_{out} - \Delta B_{in}) \frac{\Delta u_j}{\Delta y_i} \qquad (2)$$

where Δu_j denotes a step change of the *MV* u_j, Δy_i denotes a response in the *CV*, y_i, caused by a step change of u_j, and ΔB_{out} and ΔB_{in} represent the exergy differences caused by the *MV* step change for exergy out and exergy in, respectively. For example, if $\tau_{21}$is less than τ_{22}, it means that for the same amount of *CV* change Δy_2, using u_1, will cause less exergy destruction than using u_2. The final interpretation is that the control pairing (u_1, y_2) is more eco-efficient than the pairing (u_2, y_2).

C. *Relative Gain Array (RGA)*

The RGA is an array of relative gains (λ_{ij}) for all possible pairing combinations of single input single output (SISO) loops as shown in (3) [23].

$$\Lambda = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \cdots & \lambda_{1n} \\ \lambda_{21} & \lambda_{22} & \cdots & \lambda_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \lambda_{n1} & \lambda_{n2} & \cdots & \lambda_{nn} \end{bmatrix} \qquad (3)$$

where Λ = Relative gain array and λ_{ij} = relative gain for a control pair (u_j, y_i)

The relative gain, λ_{ij}, which relates the j^{th} input u_j and i^{th} output y_i, can be expressed by the following correlation,

$$\lambda_{ij} = \left(\frac{\Delta y_i}{\Delta u_j}\right)_{u_k = const,\ k \neq j} \Big/ \left(\frac{\Delta y_i}{\Delta u_j}\right)_{y_k = const,\ k \neq i} \qquad (3)$$

Relative gain is defined as the ratio of open loop process gain in an isolated loop to apparent process gain in the same loop when all other control loops are closed and are in perfect control [23]. Open loop process gain is defined as

$$k_{ij}=\left(\frac{\Delta y_i}{\Delta u_j}\right)_{u_k=const,\ k\neq j} \tag{4}$$

where k_{ij} = dimensionless open loop gain for a control pair (u_j, y_i)

The RGA provides a quantitative comparison of steady-state interactions between different possible pairing combinations of control loops. Guidelines for interpreting the RGA results and details are also given by [5, 24].

III. RELATIVE EXERGY DESTROYED ARRAY (REDA)

A. *REDA Definition*

The EEF in (2) can be re-arranged with the definitions of steady state gain and destroyed exergy during a step input as,

$$\tau_{ij}={\Delta B_D}\big/{k_{ij}} \tag{5}$$

where k_{ij} = steady state gain for a control pair (u_j, y_i) and $\Delta B_D = \Delta B_{Out} - \Delta B_{In}$ = exergy destroyed in a process during a step input.

The relative EEF (REEF) is defined as,

$$\upsilon_{ij}=\frac{\left(\tau_{ij}\right)_{u_k=const,\ k\neq j}}{\left(\tau_{ij}\right)_{y_k=const,\ k\neq i}} \tag{6}$$

The REEF Array (REEFA) is an array of REEF (υ_{ij}) for all possible pairing combinations.

$$\Upsilon=\begin{bmatrix}\upsilon_{11} & \upsilon_{12} & \cdots & \upsilon_{1n}\\ \upsilon_{21} & \upsilon_{22} & \cdots & \upsilon_{2n}\\ \vdots & \vdots & \vdots & \vdots\\ \upsilon_{n1} & \upsilon_{n2} & \cdots & \upsilon_{nn}\end{bmatrix} \tag{7}$$

Mathematically, the relative exergy destroyed (RED) is derived from the definitions of steady state gain, exergy destroyed during a step input and the definition of EEF in (4), (5) and (2) respectively. The exergy destroyed in a process during a step input is equal to the product of steady state gain and EEF for a control pair (u_j, y_i) as shown in (5). The relative exergy destroyed (ζ_{ij}) is defined from (5) as,

$$\zeta_{ij}=\frac{\left({\Delta B_D}\big/{\Delta u_j}\right)_{u_k=const,\ k\neq j}}{\left({\Delta B_D}\big/{\Delta u_j}\right)_{y_k=const,\ k\neq i}}=\frac{\left({k_{ij}\tau_{ij}}\big/{\Delta u_j}\right)_{u_k=const,\ k\neq j}}{\left({k_{ij}\tau_{ij}}\big/{\Delta u_j}\right)_{y_k=const,\ k\neq i}} \tag{8}$$

$$\zeta_{ij}=\frac{\left(k_{ij}\right)_{u_k=const,\ k\neq j}}{\left(k_{ij}\right)_{y_k=const,\ k\neq i}}*\frac{\left(\tau_{ij}\right)_{u_k=const,\ k\neq j}}{\left(\tau_{ij}\right)_{y_k=const,\ k\neq i}}=\lambda_{ij}*\upsilon_{ij} \tag{9}$$

where k_{ij} = steady state gain for a control pair (u_j, y_i), τ_{ij} = EEF for a control pair (u_j, y_i), λ_{ij} = relative gain for a control pair (u_j, y_i), υ_{ij} = REEF for a control pair (u_j, y_i) and u_j = step input.

The relative exergy destroyed is defined analogously to the original relative gain (λ_{ij}) of the RGA. The relative exergy destroyed is the ratio of the total exergy destroyed in a process due to step input (u_j) when all loops are open, to the total exergy destroyed in a process due to step input (u_j) when all other loops are closed in "perfect" control (as shown in (7) and (8)).

After we put the relative exergy destroyed (8) into matrix form, we obtain the relative exergy destroyed array (REDA) (9). It can be directly obtained through a Hadamard product of RGA and REEFA matrices as,

$$Z=\begin{bmatrix}\lambda_{11} & \lambda_{12} & \cdots & \lambda_{1n}\\ \lambda_{21} & \lambda_{22} & \cdots & \lambda_{2n}\\ \vdots & \vdots & \vdots & \vdots\\ \lambda_{n1} & \lambda_{n2} & \cdots & \lambda_{nn}\end{bmatrix}\begin{bmatrix}\upsilon_{11} & \upsilon_{12} & \cdots & \upsilon_{1n}\\ \upsilon_{21} & \upsilon_{22} & \cdots & \upsilon_{2n}\\ \vdots & \vdots & \vdots & \vdots\\ \upsilon_{n1} & \upsilon_{n2} & \cdots & \upsilon_{nn}\end{bmatrix} \tag{10}$$

$$Z=\Lambda\otimes\Upsilon \tag{11}$$

where Z = Relative exergy destroyed array (REDA), ζ_{ij} = RED for a control pair (u_j, y_i) and υ_{ij} = REEF for a control pair (u_j, y_i)

B. *Interpretation of REDA*

The REDA is a new and useful tool though based on steady state information. This new tool can be applied to a process after selecting control pairs via the RGA. The REDA compares the eco-efficiency of a process under different control structures. To understand the significance of the REDA, guidelines for interpreting the REDA results explained below should be understood.

The Sum of the elements of any row or column of the REDA is unity. ζ_{ij} is dimensionless and independent of scaling.

If $\zeta_{ij} = 0$, then the manipulated variable u_j has no effect on the eco-efficiency of that process. In this situation a step input in u_j does not increase exergy destruction. If the diagonal elements of the REDA, $\zeta_{ij} = 0$, then pair u_j with y_i.

If $\zeta_{ij} = 1$, then this implies that the manipulated variable u_j is the only variable responsible for the exergy destruction of the process. If the diagonal elements of the REDA, $\zeta_{ij} = 1$, then avoid pairing u_j with y_i.

If $0 < \zeta_{ij} < 1$, then this implies that the manipulated variable u_j is not the only variable responsible for the exergy destruction of the process. Manipulated variables other than u_j are also responsible for the exergy destruction of the process.

If $\zeta_{ij} = 0.5$, then this implies that the all manipulated variables have same effect on the eco-efficiency of the process. In this situation the final selection of control loop pairing should be based on RGA results. The ζ_{ij} value should be close to unity.

If $\zeta_{ij} > 1$, then this implies that the open loop EEF is larger than the closed loop EEF. This implies that closing the control loops causes a decrease in exergy destruction. $\zeta_{ij} >> 1$ is not favourable due to a large amount of exergy destruction during a step input in the process. The ζ_{ij} value should be close to unity.

If $\zeta_{ij} < 1$, then this implies that the open loop EEF is smaller than the closed loop EEF. Thus implies that closing the control loops causes an increase in exergy destruction. $\zeta_{ij} << 1$ is not favourable due to a large amount of exergy destruction during a step input in the process. The ζ_{ij} value should be close to unity.

Off-diagonal elements of REDA close to unity or diagonal elements of REDA close to zero are recommended.

C. Rank based on REDA

In Table 1, if the diagonal elements in both RGA and REEFA are close to one, then we use "Diagonal" to donate this situation. In the same way, we use "Off-diagonal" to represent that the off-diagonal elements in both RGA and REEFA are close to one.

Table 1: REDA rank for selecting control configuration

Configuration (RGA*REEFA) Matrices	Results	REDA
Diagonal – Diagonal	Controllable, Not Eco-efficient	Ok
Diagonal – Off-diagonal	Controllable, Eco-efficient	Best
Off-diagonal – Diagonal	Uncontrollable, Not Eco-efficient	Worst
Off-diagonal – Off-diagonal	Uncontrollable, Eco-efficient	Bad

Based on the structure (Diagonal or off-diagonal) of RGA and REEFA matrices, a ranking of options can be developed between the best and worst options as shown in Table 1. The control pair whose diagonal elements in the RGA and off-diagonal elements on the REEFA are close to 1 is the best choice (i.e. it is both controllable and eco-efficient).

IV. CASE STUDIES

A. A CSTR Example

For the explanation of REDA, a simple reactor (R1) is used with hypothetical components as shown in Figure 2.

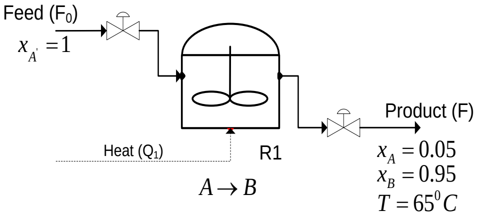

Figure 2: A simple CSTR with a hypothetical reaction, $A \to B$

In the reactor, component A is converted into component B via a simple ($A \to B$) 1st order reaction. The information about the hypothetical components and reaction is given in Table 2. F_0 denotes the fresh feed flow rate having pure A, x_A denotes the mole fraction of A, x_B denotes the mole fraction of B and F denotes the product flow rate of the mixture of A & B.

Table 2: Hypothetical components and reaction information

Hypothetical components details				Reaction Information
Component *A*		Component *B*		$r = k * x_A$ $k = A * \exp(-E/RT)$ $A = 6*10^8 kmol/m^3/s$ $E = 69,780 kJ/kmol$
NBP (^{0}C)	80	NBP (^{0}C)	110	
Molecular weight	78	Molecular weight	96	

In this process, there are two controlled variables: component B composition x_B, and temperature T, of the product. The composition and temperature of the product are affected by the feed flow rate F_0, or heat flow Q, into the reactor.

After selecting two control loops (composition and temperature control) the EEF is used to evaluate the effect of each control pair on the overall exergetic efficiency of the process. The results are listed in Table 3.

From Table 3, the control pair (F_0, x_B) will use less exergy than control pair (Q, x_B) for controlling the product stream composition (x_B) The control pair (F_0, T) uses slightly less exergy than the control pair (Q, T). In the sense of eco-efficiency, the best control pair selections for this process should be (F_0, x_B) and (Q, T).

Table 3: EEFs for the CSTR example

Control loop pairs	(F_0, x_B)	(Q, x_B)	(F_0, T)	(Q, T)
EEF (kW)	2.77 E3	1.24 E4	14.71	27.30

Table 4 shows the RGA, REEFA and REDA for this case study. RGA indicates both control loops have small interactions. From this RGA result, pairing diagonal elements ((F_0, x_B) and (Q, T)) seems to be the best candidate of pairing because the diagonal elements approach the value of 1 without exceeding it.

Table 4: RGA, REEFA and REDA for the CSTR example

RGA	*REEFA*	*REDA*
$\begin{bmatrix} 0.92 & 0.08 \\ 0.08 & 0.92 \end{bmatrix}$	$\begin{bmatrix} -0.70 & 1.70 \\ 1.70 & -0.70 \end{bmatrix}$	$\begin{bmatrix} -0.51 & 1.51 \\ 1.51 & -0.51 \end{bmatrix}$

The REEFA indicates that both manipulated variables (F_0 and Q) affect the destruction of exergy in this process. As off-diagonal elements are close to 1, therefore pairing diagonal elements ((F_0, x_B) and (Q, T)) is more eco-efficient than pairing off-diagonal elements ((F_0, T) and (Q, x_B)) as shown in Table 4.

The REDA shows that pairing diagonal elements ((F_0, x_B) and (Q, T)) gives relative exergy destroyed values close to 0 as shown in Table 4. A smaller diagonal relative exergy destroyed value of REDA implies that the process with diagonal elements pairing is more eco-efficient than the same process with off-diagonal elements pairing.

REDA with diagonal RGA and off-diagonal REEFA ranks the best option. In this situation the process pairing of diagonal elements ((F_0, x_B) and (Q, T)) is easily controllable and eco-efficient.

In this case study as off-diagonal REDA values are close to 1, therefore paired diagonal elements ((F_0, x_B) and (Q, T)) are easily controllable and eco-efficient. REDA is an off-diagonal matrix if RGA is a diagonal matrix and REEFA is an off-diagonal matrix. A diagonal RGA matrix implies that most of the interaction is between diagonal elements ((F_0, x_B) and (Q, T)), and off-diagonal elements are not much effected. The off-diagonal REEFA implies that the EEF values of their diagonal elements ((F_0, x_B) and (Q, T)) are smaller and cause less exergy destruction than the off-diagonal elements ((F_0, T) and (Q, x_B)). A REDA with off-diagonal elements close to 1 is recommended if RGA recommends pairing diagonal elements and vice versa.

B. Heat Exchanger Network (HEN) Example

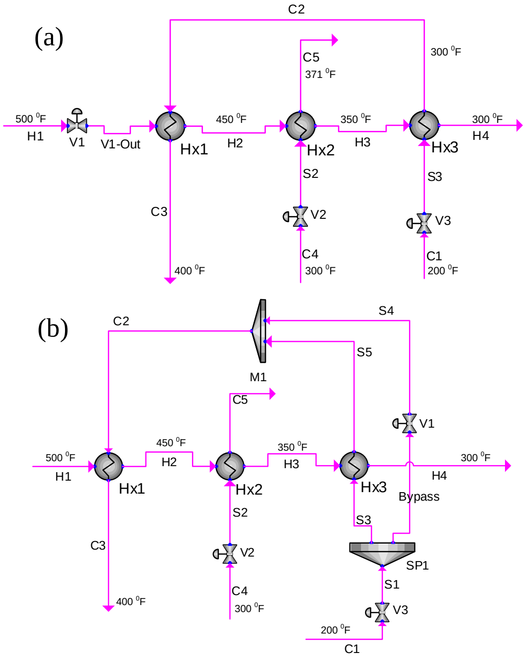

Figure 3: Heat exchanger networks: (a) Original configuration and (b) Modified configuration with bypass

In this case study, a HEN cools hot stream (H1) from 500 to 300 ^{0}F using two cold streams (C1 and C4) having temperatures of 200 and 300 ^{0}F as shown in Figure 3. This case was studied and explained in (Seider et al. 2004).

In this case study there are three temperature controls CVs (*C5* (*T*), *C3* (*T*) and *H4* (*T*) temperatures). These three CVs are controlled by manipulating the flow rates of the two cold streams (*C1* and *C4*) and hot stream (*H1*) by control valves as shown in Figure 3 (a). In an alternate/modified configuration, a bypass around heat exchanger (Hx3) is involved instead of hot steam (*H1*) manipulation. In this modified configuration, the three temperatures (*C5*(*T*), *C3*(*T*) and *H4*(*T*)) are controlled by manipulating the flow rates of the two cold streams (*C1* and *C4*) and bypass flow fraction (*S4*) as shown in Figure 3 (b).

The HEN behaves as a 3 x 3 square system in which the number of manipulated and control variables are equal and three in number. The steady state gain matrices derived/defined for the HEN for the original and modified configurations are shown in (12) and (13) respectively.

$$\begin{bmatrix} C5(T) \\ C3(T) \\ H4(T) \end{bmatrix} = \begin{bmatrix} \frac{\partial C5(T)}{\partial C4} & \frac{\partial C5(T)}{\partial C1} & \frac{\partial C5(T)}{\partial H1} \\ \frac{\partial C3(T)}{\partial C4} & \frac{\partial C3(T)}{\partial C1} & \frac{\partial C3(T)}{\partial H1} \\ \frac{\partial H4(T)}{\partial C4} & \frac{\partial H4(T)}{\partial C1} & \frac{\partial H4(T)}{\partial H1} \end{bmatrix} \begin{bmatrix} C4 \\ C1 \\ H1 \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} C5(T) \\ C3(T) \\ H4(T) \end{bmatrix} = \begin{bmatrix} \frac{\partial C5(T)}{\partial C4} & \frac{\partial C5(T)}{\partial C1} & \frac{\partial C5(T)}{\partial S4} \\ \frac{\partial C3(T)}{\partial C4} & \frac{\partial C3(T)}{\partial C1} & \frac{\partial C3(T)}{\partial S4} \\ \frac{\partial H4(T)}{\partial C4} & \frac{\partial H4(T)}{\partial C1} & \frac{\partial H4(T)}{\partial S4} \end{bmatrix} \begin{bmatrix} C4 \\ C1 \\ S4 \end{bmatrix} \tag{13}$$

Table 5 shows the RGA, REEFA and REDA results for the HEN. RGA results indicate that the leading diagonal elements of the original and modified control configurations are positive and close to 1. RGA recommends (*C5* (*T*)-*C4*, *C3* (*T*)-*C1* and *H4* (*T*) - *H1*) pairings for the original configuration and (*C5* (*T*)-*C4*, *C3* (*T*) - *C1* and *H4* (*T*) - *S4*) pairings for the modified configuration. The original and modified control configurations both are further selected to check for their eco-efficiency.

The EEF for different diagonal, off-diagonal and other control loop pairs are shown in Table 6. With the original configuration, the control pairing (*C4*, *C3* (*T*)) will use the most exergy and be the least eco-efficient control pair, and the control pairing (*C1*, *C3* (*T*)) is the most eco-efficient pairing. The sum of the EEFs for the original configuration is 630 kW. With the modified configuration (bypass), the control pairing (*S4*, *C3* (*T*)) is the most eco-efficient pairing. The sum of the EEFs for the modified configuration is 322 kW. As the sum of the EEFs for the modified configuration diagonal elements (322 kW) is less than the sum of original configuration diagonal elements (630 kW), therefore the HEN with the modified configuration is more eco-efficient than the same process with the original configuration. The modified configuration (EEF: 322 kW) can save 48% more exergy compared to the original configuration (EEF: 630kW) as calculated from Table 6.

As REEFA results for original and modified configurations show that their leading diagonal elements are away from 1 and close to 0, therefore pairing diagonal elements of the original and modified control configurations is more eco-efficient than pairing off-diagonal or other elements as shown in Table 5.

REDA results show that the HEN under the modified control configuration has leading diagonal elements (0.07, -0.24 and -0.20) more close to 0 than under the original control configuration (0.0, -0.01 and 1.10). So the HEN under the modified control configuration is more eco-efficient than under the original control configuration as shown in Table 5. This agrees with the result based on summation of the EEFs in Table 6.

Table 5: RGA, REEFA and REDA results for the HEN case study example

Configuration	RGA	REEFA	REDA
Original	$\begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & 0.65 & 0.35 \\ 0.0 & 0.35 & 0.65 \end{bmatrix}$	$\begin{bmatrix} 0.0 & 2.42 & -1.42 \\ 1.04 & 0.0 & -0.04 \\ -0.05 & -1.43 & -2.48 \end{bmatrix}$	$\begin{bmatrix} 0.0 & 1.07 & -0.07 \\ 1.04 & -0.01 & -0.03 \\ -0.05 & -0.06 & 1.10 \end{bmatrix}$
Modified	$\begin{bmatrix} 1.19 & 0.01 & -0.20 \\ 0.0 & 1.14 & -0.14 \\ -0.19 & -0.15 & 1.34 \end{bmatrix}$	$\begin{bmatrix} 0.0 & -0.01 & 1.01 \\ 1.08 & -0.08 & 0.0 \\ -0.08 & 1.09 & -0.01 \end{bmatrix}$	$\begin{bmatrix} 0.07 & -0.23 & 1.24 \\ 1.24 & -0.24 & 0.0 \\ -0.27 & 1.47 & -0.20 \end{bmatrix}$

Table 6: EEFs for the HEN case study example

	Original Configuration			Modified Configuration		
Diagonal pairs	(*C4*, *C5*(*T*))	(*C1*, *C3*(*T*))	(*H1*, *H4*(*T*))	(*C4*, *C5*(*T*))	(*C1*, *C3*(*T*))	(*S4*, *H4*(*T*))
EEF (kW）	184	101.59	343.54	184	99	39.11
Off-Diagonal pairs	(*H1*, *C5*(*T*))	(*C4*, *H4*(*T*))	(*H1*, *C3*(*T*))	(*S4*, *C5*(*T*))	(*C4*, *H4*(*T*))	(*S4*, *C3*(*T*))
EEF (kW）	874.54	460	2.63 E3	3.85 E3	920	26.01
Other pairs	(*C4*, *C3*(*T*))	(*C1*, *C5*(*T*))	(*C1*, *H4*(*T*))	(*C4*, *C3*(*T*))	(*C1*, *C5*(*T*))	(*C1*, *H4*(*T*))
EEF (kW）	1.84 E5	828	188.28	6.13 E3	227.7	189.75

V. CONCLUSIONS

A new tool, the relative exergy destroyed (REDA), was developed. The REDA integrates the controllability and measurements of eco-efficiency of a process. This new tool measures the relative eco-efficiency of a process and provides a measure which can be used to compare eco-efficiency of MIMO processes for different combinations of control structures. In other words, it compares the eco-efficiency of a process with several process control structures. It is simple and easy to use during early process design stages as it is based on steady state information.

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