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Eco-efficiency and Control Loop Configuration for Recycle Systems

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Abstract — **Given that the eco-efficiency of industrial processes/plants has become important, engineers need to find a way to integrate control loop configuration and measurements of eco-efficiency. The exergy eco-efficiency factor, a new measure of eco-efficiency for control loop configuration has been developed. The exergy eco-efficiency factor is based on the thermodynamic concept of exergy which can be used to analyze a process in terms of its efficiency. The combination of the Relative Gain Array (RGA), NI, CN, dynamic RGA, Relative exergy gain array (REA) and the exergy efficiency factor will help guide the process designer to find the optimal control design with low operating cost/eco-efficiency. In this paper, we validate the proposed eco-efficiency factor for the common industrial situation involving recycle streams.**

I. Introduction

For a decentralized control system, control loop configuration or control pair selection focuses on selecting the best control scheme for pairing manipulated and controlled variables. 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)[1, 2].

Nowadays, in the wake of the energy crisis, control loop configuration can not only focus on control loop analysis techniques alone such as control loop stability analysis and consideration of the quality of the controller variable, but must also include energy cost and environmental impact. In most control loops, exergy plays an important role since it can be used for determining the exergetic efficiency and sustainability of a process [3] and environmental impacts can be minimized by reducing exergy losses [4, 5]. As exergy accounts for the quality of energy, it can be used to evaluate the eco-efficiency for a process.

Thermodynamic properties like exergy also have the potential to be used for the development of process control structures. A basic framework for the development of a dynamic exergy balance for process control evaluation has been proposed in [6]. The Relative Exergy Array (REA) was subsequently developed based on analyzing the exergy interactions for the control configuration within the process design, [7, 8]. Some research has also been done on process control effects on entropy production [9, 10].

In this paper, we will extend the eco-efficiency analysis of the control loop configuration into the whole unit/process or even plant. A new measure of eco-efficiency, the exergy efficiency factor (EEF), is proposed.

For a general multi-input-multi-output (MIMO) process, a certain amount of exergy consumption/generation is needed to change one controlled variable (CV) by using one manipulated variable (MV). The exergy efficiency factor is 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 most eco-efficient control pairing. Combining the analysis from established control loop configuration methods such as RGA, NI and SVD with the proposed new measure EEF, engineers can select the best control configuration for both controllability and eco-efficiency.

It is a common practice to recycle material and energy streams in the chemical process industry. While recycling improves the material usage and energy efficiency in the case of an individual unit like a distillation column, it can change the controllability and eco-efficiency of that unit significantly. The eco-efficiency factor is used to select the most eco-efficient control configuration for a process with recycle. The EEF also is employed to provide the exergy difference between the process with and without recycle. The results for EEF are validated by the dynamic simulation.

This manuscript is organized as follows. After this general introduction, the concept of eco-efficiency is introduced, the exergy efficiency factor is proposed and its validation is explained. Then, the proposed method is implemented for a simulation example. Finally, the results are discussed and conclusions are made in the summary.

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II. CONTROL PAIR SELECTION

A. Methods Based on Controllability

Different researchers have investigated the effects of recycles on controllability - for example it is known that the RGA of an isolated individual distillation column is different to the RGA of the same column in a plantwide layout with recycle [11]. Luyben worked on several case studies with recycles and explained the remedy for the high gain in recycle flow and proposed to fix a flow in the recycle loop [12]. The impact of recycle on the dynamics of the process and snowball effect was explained [6]. The effect of recycle on controllability for the ethyl benzene production plant was investigated [13].

The use of the RGA [14] was originally used for establishing optimal control loop pairings as for example in a distillation column [15]. Extensions include the dynamic RGA [16, 17] and the effective relative gain array [18]. The Niederlinski index (NI) is used for testing the stability of RGA selected control loop pairings [19]. Singular Value Decomposition (SVD) is a useful tool to check whether the control loop interactions are sensitive to small errors in process gains and indicates if the control loops may be decoupled. The condition number (CN), which is the ratio of the largest to the smallest singular values of the diagonal matrix of eigenvalues indicates if decoupling is feasible or not [2, 20].

B. Methods Based on Eco-Efficiency

According to the World Business Council for Sustainable Development (WBCSD) definition, eco-efficiency is achieved through the delivery of *"competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing environmental impacts of goods and resource intensity throughout the entire life-cycle to a level at least in line with the Earth's estimated carrying capacity."* This concept describes a vision for the production of economically valuable goods and services while reducing the ecological impacts of production. In other words eco-efficiency means producing more with less.

When applying the concept of eco-efficiency to control loop configuration, we need to develop 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 eco-efficiency factor is proposed (Section III contains further, detailed information).

In every chemical process there are some materials coming in or going out. Similarly, every process needs some energy to perform its work and/or the process rejects energy to the surroundings. So the material and energy balances of the process are generally used to evaluate the efficiency of the process at the process design stage. Thermodynamic laws (1^{st} and 2^{nd}) may give an idea about process efficiency, energy loss, work done, required work and entropy production. For energy efficiency of a process, inputs, outputs and losses are defined in terms of energy [21]. The combination of the 1^{st} and 2^{nd} laws of thermodynamics gives rise to the concept of exergy which is the basic measure of eco-efficiency. Exergy is the maximum possible amount of work which can be drawn from a material stream when it interacts only with the environment as it comes from its initial state to the final dead state [22, 23].

III. ECO-EFFICIENCY FACTOR OF THE MANIPULATED VARIABLE

Exergy and calculations involving it and its different components are explained in [24, 25]. Exergetic efficiency, η, is defined as the ratio of the exergy going out to the exergy going into a process [26],

$$\eta = B_{out} / B_{in} \tag{1}$$

where η is the exergetic efficiency, B_{out} is the total exergy going out of a process and B_{in} is the total exergy coming in to a process.

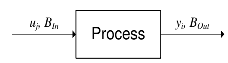


Fig. 1: A general process

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 in Fig. 1. The definition of total exergy and detailed exergy calculation procedures using the simulator software VMGSim can be found in [24, 27].

Equation (1) 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. In this paper we propose a new measure, exergy eco-efficiency factor, which connects the control loop configuration to the eco-efficiency. The EEF for a control pair (u_j, y_i), is defined as,

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

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 the *MV*, 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 *MV*, u_1, will cause less exergy than using *MV*, 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).

In plant-wide layouts the presence of recycle can also have a significant effect on the control configuration selection of a unit. The final selection of a control configuration should be based on plant-wide layout. After selection of a control configuration, the proposed method of exergy eco-efficiency factor is applied and validated by dynamic simulation. The use of exergy efficiency factor is illustrated by a process simulation case study.

As the recycling improves energy efficiency, therefore it also has an impact on the exergy eco-efficiency factor. The Exergy efficiency factor decreases for a unit when it is considered with recycle and vice versa. Recycle of material and energy reuses energy, which decreases the destruction of exergy. In the exergy efficiency factor equation (2), the term in brackets accounts for the exergy destruction. If exergy destruction is small then this term in brackets would be small, which means the exergy efficiency factor is small. A smaller value of exergy efficiency factor for units with recycles means a more eco-efficient process.

Usually control loop configuration is determined by techniques such as RGA and NI. It is usual that several candidate control loop configurations can be used. Our new exergy efficiency factor can be used to select the best control loop configuration among the candidates in the sense of eco-efficiency.

IV. VALIDATION OF THE EXERGY EFFICIENCY FACTOR

Dynamic simulation is the best way to validate the proposed eco-efficiency factor. By recording the exergy consumptions of several control configurations, we can identify the most eco-efficient control configuration and compare the dynamic result to the result from the eco-efficiency factor.

Dynamic exergy versus time trends can be approximated by several exergy calculations at different conditions during the dynamic response of a process. As most chemical simulators still do not have the ability to directly calculate the total exergy of a material stream, these simulators cannot calculate exergy at every point versus time automatically. Simulators such as HYSYS and VMGSim can only calculate steady state exergy values at given process conditions. For dynamic exergy versus time, different points are selected during the process dynamic response due to step input disturbances. To reduce the computation, selection of calculation points depend on the process response. It means that when the outputs changes are dramatic, the sampling interval is short; otherwise the sampling interval is large. Then the exergy values are calculated on those selected points during the dynamic process response. Exergy values at different points are calculated with the procedure developed [27]. Then those exergy points are used to approximate the dynamic exergy response versus time.

V. CASE STUDY

For this case study a monochlorobenzene (MCB) separation process is selected from [2]. It consists of three main parts: a flash vessel (F1), an absorption column (T1) and a distillation column (T2) as shown in Fig. 2.

The feed of this process consists of a mixture of monochlorobenzene (MCB), benzene and HCl. The vapor stream coming out of the flash tank is fed into the absorber where it is contacted with recycled MCB. Most of HCl product comes out of the absorber as vapor. The liquid product (L2) coming out of the absorber is mixed with liquid product (L1) of the flash vessel in a mixer (M1). The mixture coming out of the mixer (M1) is then fed into the distillation column (T2). In this column a fixed amount (1% of inlet feed to the plant) is purged from the process to avoid HCl build-up in the system. The distillate product (*D*) contains most of the benzene and bottom product (*B*) contains most of the MCB. Some fraction of bottom product stream is recycled back into the absorber.

VMGSim with the NRTL activity thermodynamic model is used for this simulation of the MCB separation process. The detailed information of the feed conditions and column specification can be found in [28].

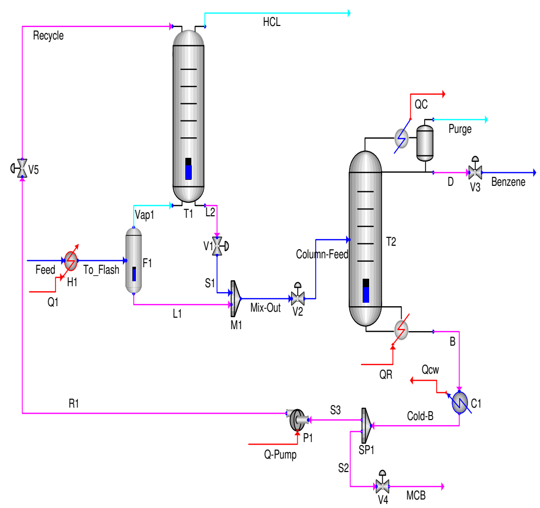


Fig. 2: MCB separation process schematic

In practice, the control configurations are the same during startup and operational periods. Control configurations should work fine during both periods for the final selection of a control configuration. As the distillation column is ultimately fitted with other units and recycles in a plantwide layout therefore the final selection of a control configuration is based on RGA, DRGA, REA, NI and CN for the column in a plantwide layout. The results of an isolated distillation column are not reliable as these can work fine during startup period but not during the operational period of the plant.

In this case study, there are three composition control loops. The composition of HCl (x_{HCl}) leaving in the vapor stream of the absorber is controlled by manipulating the cooler (*C1*) duty (Q_{cw}). The compositions at the top and bottom of the distillation column, x_D and x_B, are the other two controlled variables with x_{HCl} composition. For this three-point composition control of the MCB separation plant, three basic control configurations: LVQ_{cw}, LBQ_{cw} and DVQ_{cw} are considered. For example, in the LVQ_{cw} control configuration, *L (Reflux rate)* is used to control the composition of the top product, x_D, boil-up rate (V) is used to control the composition of the bottom product, x_B, and cooler duty (Q_{cw}) is used to control the composition of vapor stream leaving the absorber [28]. The simulation results are listed in Table 1.

From Table 1, the RGA results show that the leading diagonal elements of the LVQ_{cw} and LBQ_{cw} control configurations are positive, although quite large for LVQ_{cw}. The RGA results of the DVQ_{cw} control configuration are far away from 1 except for one element. The Dynamic Relative Gain Array (DRGA) results are interesting, showing that the leading diagonal elements of the LVQ_{cw} control configuration are positive although quite large. The DRGA results for the LBQ_{cw} and DVQ_{cw} control configurations are also different to the results of the steady state RGA analysis. From Table 1, the DRGA results show that the leading diagonal elements of the DVQ_{cw} control configuration are positive and close to 1. The NI results of the LVQ_{cw} and DVQ_{cw} control configurations are positive which is favorable. The CN of the LVQ_{cw} and DVQ_{cw} control configurations is less than 50; this indicates that the LVQ_{cw} and DVQ_{cw} control loops can be decoupled and are not sensitive to small errors in process gains. The LBQ_{cw} control configuration is not further selected as its DRGA leading diagonal elements are significantly away from 1 which is not acceptable, and the NI result for the LBQ_{cw} control configuration is negative which indicates instability of the system.

Table 1: RGA, DRGA, REA, NI and CN Results

Configuration	LVQ_{cw}	LBQ_{cw}	DVQ_{cw}
RGA	$\begin{bmatrix} 6.3 & -4.76 & -0.54 \\ -5.8 & 6.5 & 0.35 \\ 0.52 & -0.7 & 1.2 \end{bmatrix}$	$\begin{bmatrix} 0.88 & 0.1 & 0.02 \\ 0.12 & 0.92 & -0.05 \\ 0 & -0.03 & 1.02 \end{bmatrix}$	$\begin{bmatrix} 0.52 & 0.49 & -0.01 \\ 0.39 & 0.51 & 0.1 \\ 0.1 & 0 & 0.91 \end{bmatrix}$
DRGA	$\begin{bmatrix} 3.8 & -2.8 & 0.02 \\ -1.4 & 2.6 & -0.23 \\ -1.4 & 1.2 & 1.2 \end{bmatrix}$	$\begin{bmatrix} 0.84 & -1.6 & 1.76 \\ 0.18 & 0.38 & 0.43 \\ -0.03 & 2.2 & -1.19 \end{bmatrix}$	$\begin{bmatrix} 0.91 & 0.03 & 0.06 \\ 0.03 & 1.02 & -0.05 \\ 0.06 & -0.05 & 0.99 \end{bmatrix}$
REA	$\begin{bmatrix} 0.006 & -0.25 & 1.25 \\ 1.21 & -0.23 & 0.02 \\ -0.21 & 1.48 & -0.27 \end{bmatrix}$	$\begin{bmatrix} 0.88 & 0.13 & -0.007 \\ 0.12 & 0.61 & 0.26 \\ -0.002 & 0.26 & 0.74 \end{bmatrix}$	$\begin{bmatrix} 0.11 & 0.85 & 0.03 \\ 0.83 & 0.14 & 0.03 \\ 0.05 & 0.006 & 0.94 \end{bmatrix}$
NI	1.15	-1.0	0.97
CN	31.01	16.07	23.62

From Table 1, the REA results for the LVQ_{cw} and DVQ_{cw} control configurations show that their leading diagonal elements are far away from 1 except for one element of the DVQ_{cw} control configuration, which shows that major exergy interaction does not occur in between the diagonal elements. The results of REA can also change significantly when an individual unit is considered in a plantwide layout. The effect of recycle on REA is also studied [29].

Exergy analysis of MCB separation plant shows that most of exergy of this plant is destroyed in the distillation column [30]. To minimize this exergy destruction in the column, a control configuration is required which can decrease the exergy destruction in this column.

Based on the analysis from RGA, DRGA, NI, CN and REA, either of the LVQ_{cw} and DVQ_{cw} control configurations can be used to control this MCB separation plant, with pros and cons for both schemes. Through comparing the exergy destruction using the proposed eco-efficiency factor, we can determine the best control configuration in the sense of eco-efficiency which may help us choose between the two configurations. The eco-efficiency factors in (2) for the MCB separation plant shown in Fig. 2 are calculated using VMGSim simulations and are listed in Table 2.

Table 2: Exergy eco-efficiency factors for the column in the plantwide layout

Control Pairings	EEF (kW)
(L, x_D)	3.18 E4
(D, x_D)	652
(V, x_B)	1.22 E5
(B, x_B)	2.19 E4

From Table 2, the control pairing (V, x_B) will use the most exergy and be the least eco-efficient control pair, and the control pairing (D, x_D) is the most eco-efficient pairing. The sums of the EEFs for the LVQ_{cw} and DVQ_{cw} control configurations are 1.77 and 1.44 (×E5 kW) respectively. So both LVQ_{cw} and DVQ_{cw} control configurations are controllable but the process with a DVQ_{cw} control configuration is more eco-efficient than the same process with a LVQ_{cw} control configuration. The DVQ_{cw} control configuration can save up to 19% exergy comparing to the LVQ_{cw} control configuration. Exergy destruction involved in the control pairing (Q_{cw}, x_{HCl}) is the same for both configurations (LVQ_{cw} and DVQ_{cw}).

We will use the exergy efficiency factor to show how much exergy can be saved by using the recycle. The EEFs for the MCB separation without the recycle are listed in Table 3.

Table 3: Exergy eco-efficiency factors for the column alone

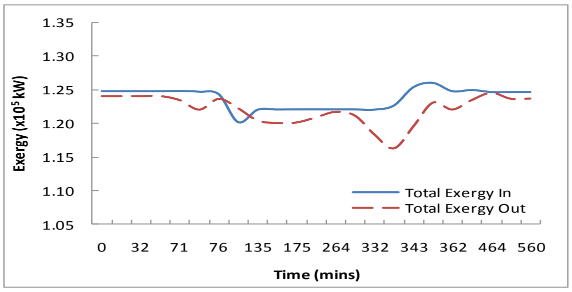
Control Pairings	EEF (kW)
(L, x_D)	3.28 E5
(D, x_D)	691.05
(V, x_B)	6.43 E5
(B, x_B)	2.91 E4

The sums of the EEFs for the LVQ_{cw} and DVQ_{cw} control configurations are 10 and 6.7 (×E5 kW), respectively. If the DVQ_{cw} control configuration is implemented for the MCB separation plant shown in Fig. 2, the recycle can save 19% in exergy.

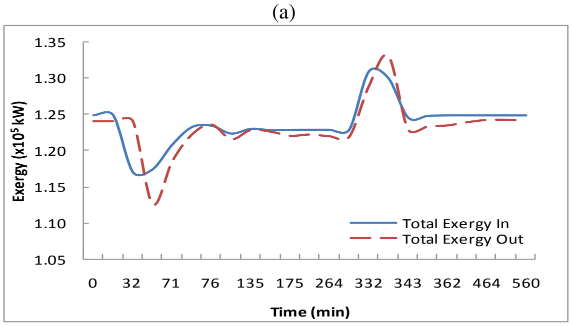
For the validation of exergy eco-efficiency factors, a dynamic model for the distillation column with recycle is built. We implemented the PI controllers for the two (LVQ_{cw} and DVQ_{cw}) control configurations along with inventory controls. Trial and error tuning was used to determine the best tuning for this simulation and the PI controller parameters are listed in Table 4. In the plant-wide layout, a bottoms product fraction is recycled back to the top of the absorber. Material and energy are reused due to the recycling of bottom product, which improves the exergy efficiency of the process. Improved exergy efficiency of the process decreases the amount of exergy destruction and exergy efficiency factors of the considered process as shown.

For each control configuration, the set points of CVs x_D and x_B are changed one by one and by the same amount (±

5%). The dynamic exergies in and out of this distillation column are approximated by the proposed method. Fig. 3 and Fig. 4 show the total dynamic exergies in and out of the distillation column in the plantwide layout for the two control configurations LVQ_{cw} and DVQ_{cw}, respectively. Fig. 3 (a) and 3 (b) show the dynamic exergies in and out of the column under LVQ_{cw} control due to a step change in the set points of *CVs* x_D and x_B, respectively. Similarly Fig. 4 (a) and 4 (b) show the dynamic exergies of the column under DVQ_{cw} control.

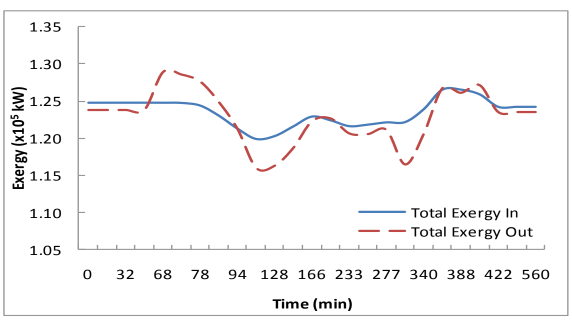


(a)

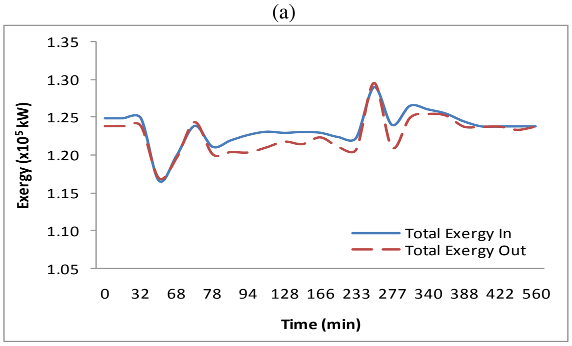


(b)

Fig. 3: Variation of Exergy In and Out due to composition set point changes for the LVQ_{cw} configuration (a) Exergy variation due to step change in x_D (b) Exergy variation due to step change in x_B



(a)



(b)

Fig. 4:Variation of Exergy In and Out due to composition set point changes for the DVQ_{cw} configuration (a) Exergy variation due to step change in x_D (b) Exergy variation due to step change in x_B

Table 4: PI controller parameters for distillation column

Control loops	LVQ_{cw} configuration		$DV\ Q_{cw}$ configuration	
	K_c	T_i*(min)*	K_c	T_i*(min)*
Feed flow control	*2.6*	*2*	*3*	*2*
Overhead pressure control	*3.3*	*0.6*	*3*	*0.5*
Condenser level control	*2*	*26*	*2*	*20*
Reboiler level control	*2*	*30*	*2*	*30*
x_D Composition control	*5*	*20*	*5*	*23*
x_B Composition control	*6.3*	*10*	*7*	*10*

The total exergies for the entire 560 min time period of the test are listed in Table 5. From Table 5, the total destroyed exergy for the whole column is 4.72×10^7 kW under DVQ_{cw} control. Compared to LVQ_{cw} control, DVQ_{cw} control can save up to 24% in exergy. This conclusion agrees with the result (save 19% in exergy) from the exergy efficiency factor analysis.

Table 5: Exergy used by the two control configurations LVQ_{cw} and DVQ_{cw}

Control Configuration / Exergy($\times10^7$kW)		LVQ_{cw}	DVQ_{cw}
step change in x_D	Total exergy in	7.24	7.19
	Total exergy out	5.97	6.13
	Destroyed exergy	1.27	1.06
step change in x_B	Total exergy in	10.3	10.42
	Total exergy out	9.8	6.76
	Destroyed exergy	5.0	3.66
	Total exergy destroyed	6.27	4.72

VI. CONCLUSIONS

The selection of a control configuration can change significantly depending on whether it is consider alone or within a plantwide layout. The selection of control configuration for a unit should be based on results when that unit is considered within the plantwide layout. Exergy efficiency factor, a new measure, for integrating control loop configuration and eco-efficiency is proposed in this paper. The exergy efficiency factor decreases due to recycle of material and energy since recycling of material and energy decreases the exergy destruction within a process. The case study result shows that the exergy efficiency factor can provide a qualitative and quantitative measure to guide engineers to select the most eco-efficient control configuration.

A higher level of efficiency is obtained if a process is controllable and thermodynamically efficient, which provides another trade-off to consider. Achieving eco-efficiency at the cost of controllability may not be acceptable, making it multi objective issue.

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