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To cite this article: Hao Jin *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **563** 052097

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# Multiobjective Optimization of Single-slide Linear Induction Motors using Kriging Surrogate Model

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**Abstract**—As electromagnetic devices, linear induction motors can produce powerful linear motion directly, which have been applied to high power system such as railway traction, electrodynamic vibrator, numerically controlled machine. The performance of linear induction motors correlates with the structural parameters of motors nonlinearly. In order to pursue better performance of the motors, a highly efficient surrogate model called kriging is implemented to address with the multi-objective optimization for the motors. This paper mainly focuses on optimizing a single-sided linear induction motor in order to improve several objectives of this motor including improving its trust and efficiency as well as losing its weight.

## 1. Introduction

Single-sided Linear induction motors (SLIM) <sup>[1]-[3]</sup> are electromagnetic devices of directly converting electrical energy into mechanical energy to realize linear motion without any mechanical converters, which have been applied in various industries. The topology of the proposed SLIM which consists of a three-phase primary and an aluminium sheet laid on the secondary back iron is depicted in Figure 1.

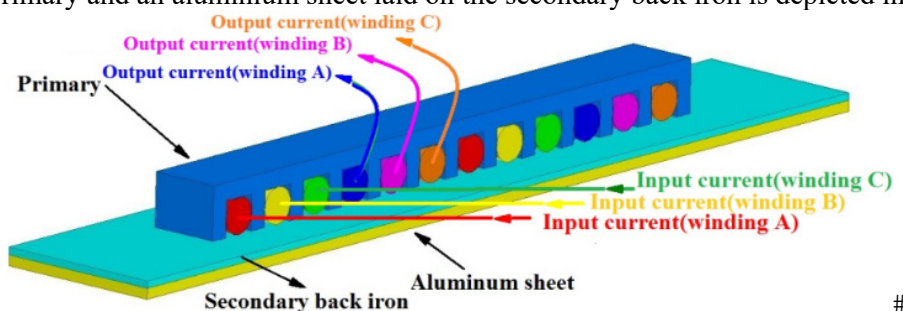


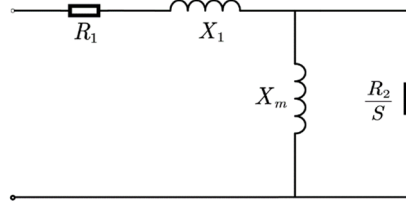
Figure 1. The topology of a SLIM

Two critical indices — efficiency and thrust indicate the performance of motors and the ratio of energy consumption <sup>[4]-[7]</sup>. For finding the optimum design parameters, a multi-objective optimization problem considering efficiency and thrust is defined <sup>[8][9]</sup>. As a reliable optimization tool, the modified kriging surrogate model with low computational cost and good accuracy of searching the global optimum design is utilized to deal with this multiobjective optimization problem.



## 2. SLIM performance from ECM

The approximate equivalent circuit of a LIM is presented as shown in Figure 2.



**Figure 2.** Equivalent circuit model for SLIMs

This circuit is on a per phase basis. The core losses are neglected because a realistic airgap flux density leads to moderate flux densities in the core and hence, rather low core losses. Skin effect is small at rated frequency for a flat linear induction motor with a thin conductive sheet on the secondary<sup>[10]</sup>. Therefore, equivalent rotor inductance is negligible. Symbols are defined on Appendix.

$$R_1 = \rho_w \frac{2(W_s + l_{ce})N_1}{A_{wt}} \quad (1)$$

$$X_1 = \frac{2\mu_0 \pi f \left[ \left( \lambda_s \left( 1 + \frac{3}{p} \right) + \lambda_d \right) \frac{w_s}{q_1} + \lambda_e l_{ce} \right] N_1^2}{p} \quad (2)$$

$$X_m = \frac{24\mu_0 f (W_s + g_m + d) k_w N_1^2 \tau}{\pi p g_e} \quad (3)$$

$$R_2 = \frac{X_m}{G} \quad (4)$$

where, the goodness factor G is defined as:

$$G = \frac{2\mu_0 f \tau^2}{\pi \left( \frac{\rho_r}{d} \right) g_e} \quad (5)$$

Thrust:

$$F_s = \frac{P_o}{V_r} = \frac{m I_1^2 R_2}{\left[ \frac{1}{(SG)^2} + 1 \right] V_s S} \quad (6)$$

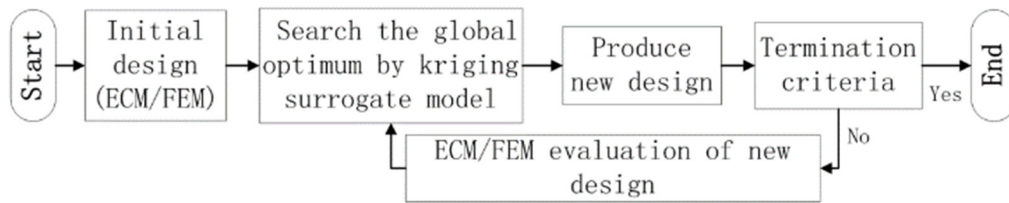
Efficiency:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{m I_2^2 R_2 \left( \frac{1-S}{S} \right)}{F_s V_s + m I_1^2 R_1} \quad (7)$$

## 3. Optimum design of SLIM using kriging surrogate model

### 3.1 Kriging surrogate model

As a kind of surrogate model, kriging can predict the shape of the objective function via spatial correlation of data using limited information. Many modifications of the kriging surrogate model presented in our previous work<sup>[11]</sup> allow efficient and robust solution of large scale and multi-parameter optimization task. The expected improvement (EI)<sup>[12]</sup> is employed to assist the kriging surrogate model in balancing the exploration and exploitation during the optimization process. The specific optimization procedure based on kriging is shown in Figure 3.



**Figure 3.** The simplified flowchart of the optimization using the kriging surrogate model<sup>#</sup>

### 3.2 Effect of design parameters on the performance of the SLIM with kriging optimization

The efficiency and thrust of SLIMs are set as the critical indices of qualifying optimal solution. To improve the efficiency and thrust, the effect of design parameters (including the air gap length, the frequency and current density of the three-phase input current, the thickness of the secondary conducting plate and so forth) on the performance of motors needs to be exposed and analyzed. The feasibility and reliability of kriging surrogate model has been verified via a large number of numerical tests and practical electromagnetic design problems. Two pairs of design parameters of SLIMS are selected to demonstrate the effect on efficiency and thrust respectively by changing these design parameters' value, meanwhile the kriging surrogate model is applied to search the optimum design parameters. The main desired specification and main fixed design parameters are given in the Table 1.

Slip rate determines the depth of field penetration and affects the secondary equivalent circuit, thus it is effective on the efficiency and thrust. As one of effective parameters on motor performance, an increment in air gap length leads to lower efficiency and small thrust. Moreover larger air gap (AG) arises more magnetizing current thus more losses in exiting rail. The thickness of conducting plate (CPT) is nonlinearly related with the efficiency and thrust. The kriging surrogate model with EI is applied to optimize those corresponding objective function, which shows the changes in efficiency and thrust by changing CPT and slip are shown in Figure 4(a) and Figure 5(a) respectively.

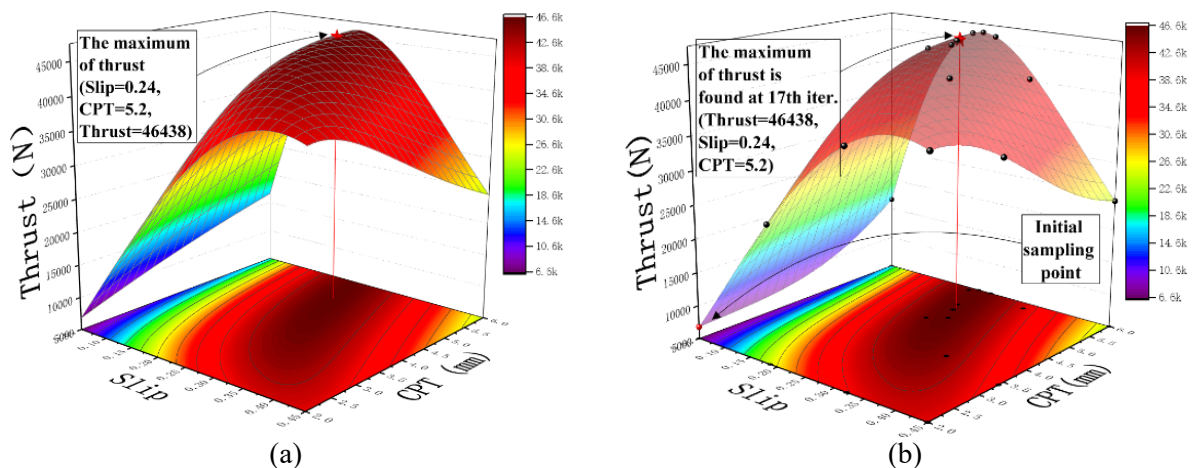
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**Table 1.** The nominal value of design parameters.

Parameter	Value
Line-to-line voltage (v)	480
Frequency (Hz)	60
Speed (m/s)	15.5
The number of poles	4
The number of slots	48
Rate slip	0.05

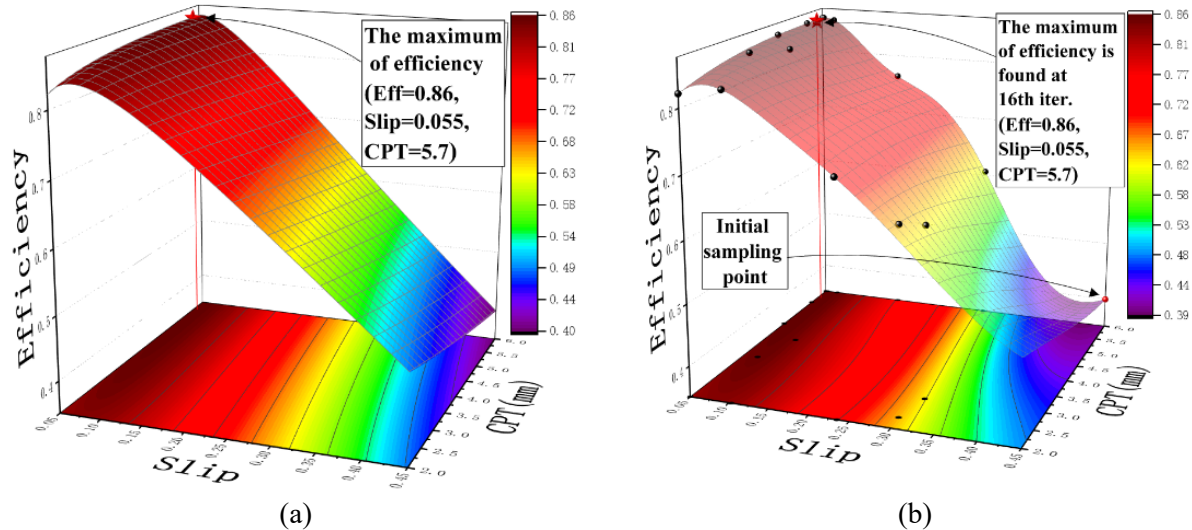
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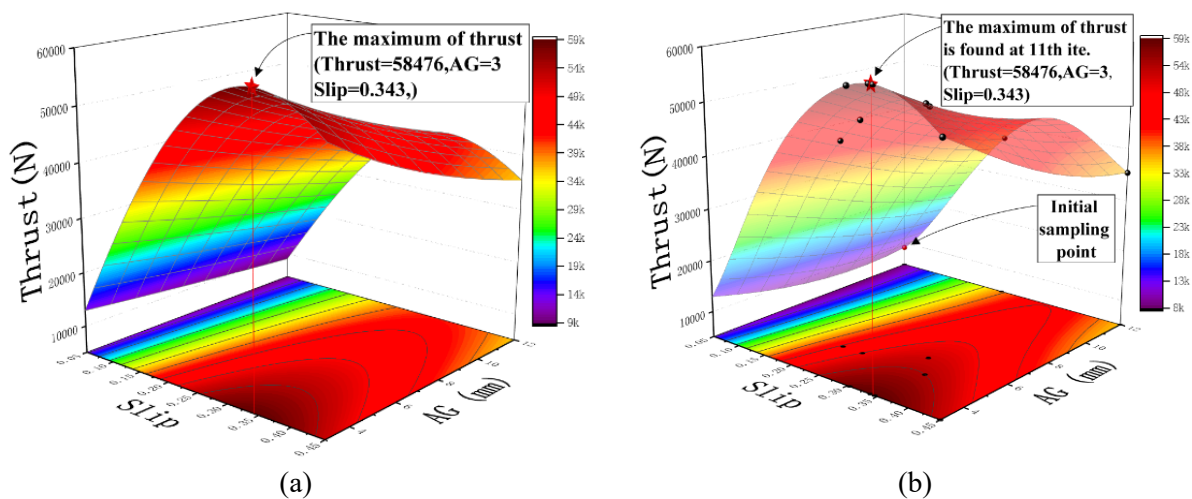


**Figure 4.** (a) Thrust versus CPT and slip; (b) Optimization based on the kriging surrogate model.

The optimal range of AG and CPT is defined as  $3(\text{mm}) \leq \text{AG} \leq 12(\text{mm})$  and  $2(\text{mm}) \leq \text{CPT} \leq 6(\text{mm})$  initially; the step size is set as  $0.1(\text{mm})$  respectively. In order to increase the difficulty of tests, the design parameters with the worst value of objective function is selected as one of two initial sample. The kriging surrogate model only required 18 calls of ECM (including the initial sample) to find the optimum design (Slip=0.24 mm, CPT=5.2 mm, thrust=46438N) in Figure 4(b). Similarly, the kriging model spends 17 ECM calls finding the global optimum when coping with the objective function about efficiency in Figure 5(b). The kriging surrogate model performs highly efficiently and accurately when locating the global optimum of objective function.

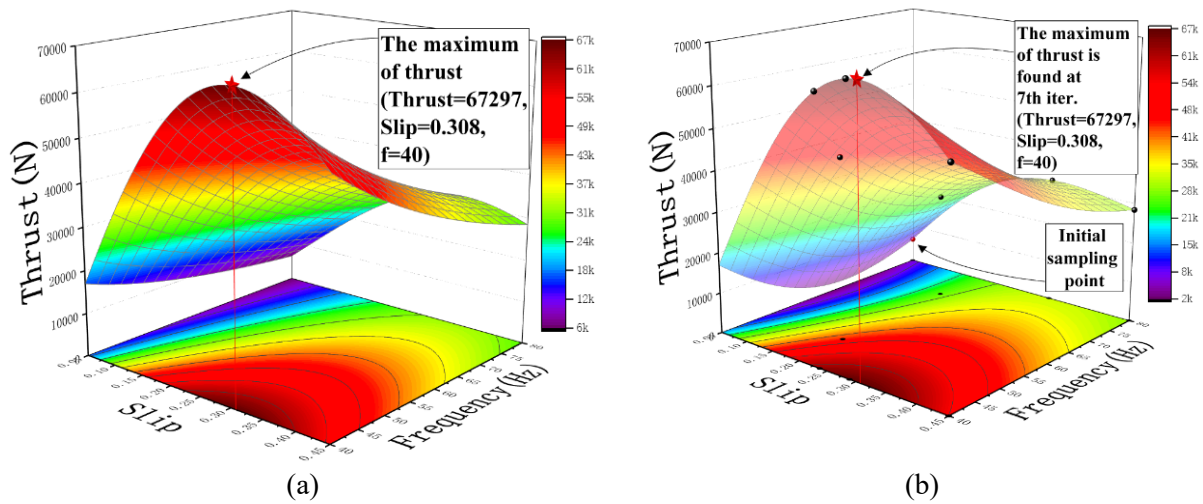


**Figure 5.** (a) Efficiency versus CPT and Slip; (b) Optimization based on the kriging surrogate model.

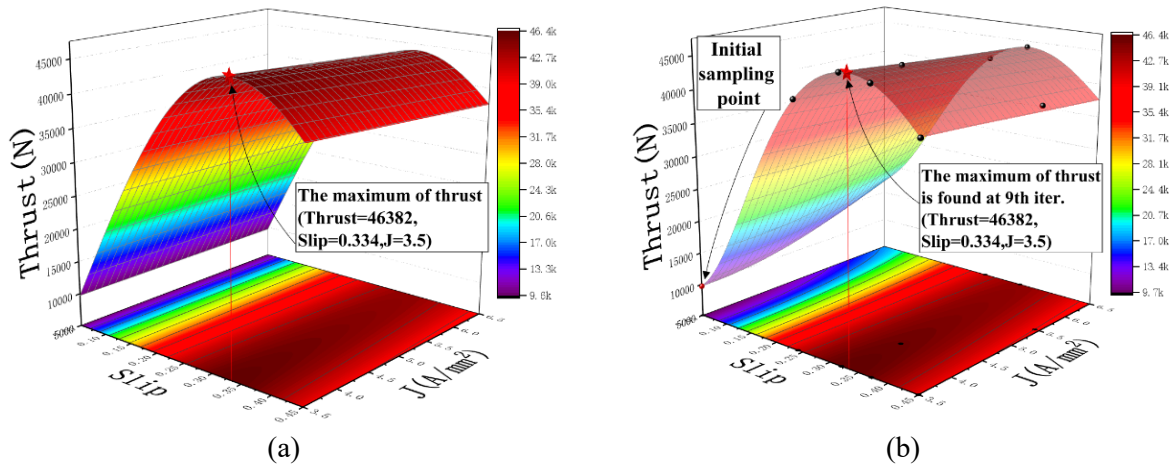


**Figure 6.** (a) Thrust versus air gap width and slip; (b) Optimization based on the kriging model.





**Figure 7.** (a) Thrust versus frequency and Slip; (b) Optimization based on the kriging model.



**Figure 8.** (a) Thrust versus frequency and current density; (b) Optimization by the kriging model.

In addition, variation in frequency at constant ratio leads to the variation on other relevant design parameters such as pole pitch, slip and field penetration depth; current density variation arises to the variation in the slot area and copper volume in the windings. Therefore, both frequency and current density affect the efficiency and thrust obviously and their influence is shown in Figure 7(a) and 8(a). The kriging surrogate model still performs efficiently and only needs 7 and 9 calls of ECM to locate the global optimum of these two objective functions respectively in Figure 7(b) and Figure 8(b). Considering the computational cost of finite element model (FEM), the ECM is firstly utilized to observe the effective design parameters on the performance of motor and verify if the kriging surrogate model is able to solve the corresponding optimization tasks. In our previous work <sup>[11][12]</sup>, the capability of kriging surrogate model has been verified through various challenging numerical tests with high irregularity. Via the above four examples, the kriging surrogate model is also able to cope with relatively smooth objective function.

#### 4 The 6-parameter optimum design of SLIM

In the previous section, the simultaneous effect of two design parameters on the output characteristics and the optimum designing obtained by the kriging surrogate model is investigated. One 6-parameter optimization task is defined to investigate the accuracy and efficiency of kriging surrogate model. The specific optimization constraints are given in Table 2.

**Table 2.** Optimization constraint

Parameter	min	max	Step size	No of steps
AG (mm)	3	12	1	10
CPT (mm)	2	6	0.1	41
J (A/mm <sup>2</sup> )	3.5	6.5	0.1	31
Frequency	40	60	1	41
SPSW	1.4	2.4	0.1	11
CRAR	0.6	1	0.04	11

(SPSW: slot pitch to slot width; CRAR: Conducting plate resistivity to aluminium resistivity)

The objective function including three optimization objectives is defined as:

$$\text{Maximize: } OF = (thrust^i + efficiency^j) / weight^k \# \quad +, \#$$

The parameter i, j and k in the above formula is the weight assigned to the corresponding output characteristic in the objective function (OF). In this section, the values of these three weighting parameters are all set as 1. The kriging surrogate model with EI finally requires 187 calls of ECM to locate the global optimum as shown in Table 3. Compared with full-scale tests which needs 63054310 times of tests in Table 2, the kriging model performs efficiently in searching optimum. To verify the validity of the optimum mainly depending on the accuracy of the circuit model, the 2-D time stepping FEM model with the same setting of design parameters' value in Table 3 is used to compare the results obtained by the ECM. It is shown that only minor difference exists between them in Table 4, thus the ECM as a computationally cheap tool the ECM is able to provide relatively accurate optimization results.

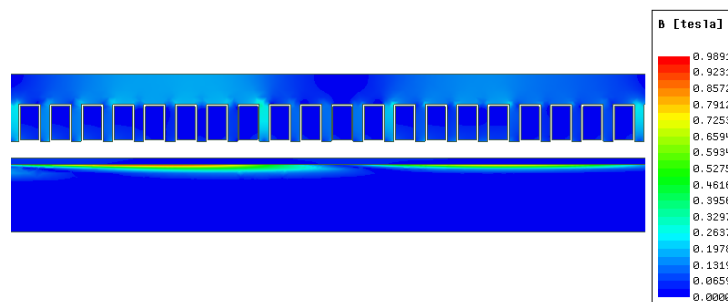
**Table 3.** The optimized design parameters obtained by the kriging optimizer

Parameter	Value	Parameter	Value
Efficiency	0.83	AG (mm)	3
Thrust (N)	9658	CPT (mm)	3
Frequency	60	J (A/mm <sup>2</sup> )	6.5
SPSW	1.4	CRAR	1
Primary weight (kg)	528.9	Copper weight (kg)	111.85

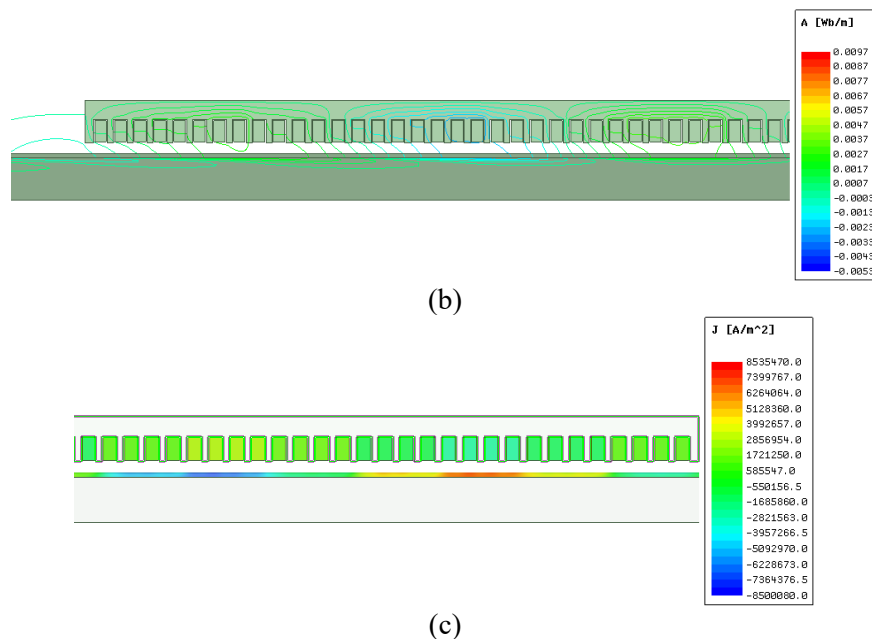
Figure 9 (a), (b) show the flux density distribution and flux lines in the 2D FEM model respectively. The flux density of conducting plate is less than 0.8T averagely that is closed to the flux density within the air gap. As the primary moves to right horizontally, the flux density reduced obviously in the front edge of the plate. Along with the increment of speed, this end effect becomes more obvious. In our future work, the research of high-speed case will be put more emphasis.

**Table 4.** Comparison between ECM and FEM analysis

Performance	ECM	FEM
Thrust (N)	9658	9445
Efficiency	0.83	0.77



(a)



**Figure 9.** (a) Flux density distribution in SLIM, (b) Flux lines in SLIM, (c) Current density in SLIM.

## 5 Conclusions

The multivariable multi objective optimization of a single-sided induction linear motor was demonstrated in this paper. In order to optimize this motor, a modified equivalent circuit model was selected to observe the effect of design parameters on the output characteristics (mainly including the efficiency, thrust and weight). As one of the advanced optimizers, the kriging surrogate model with EI developed in our previous work is employed to optimize the linear motor. Finally, validity of the optimum design obtained by the ECM was verified by 2-D FEM simulations, in order to show the accuracy of the optimum results.

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