On A Decoupled Integrated Design Approach to Robotic Mechanisms

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Abstract—Many mechatronic system design problems are formulated into a multi-objective optimization model. In such a model, multiple objectives with their weights and all variables that describe a designed system from different perspectives (such as kinematic motion, shaking force, controller) are put together and equally updated to seek an optimum. In this paper, such a model is called multiple objective concurrent design (MOCD). We argue that the MOCD model has some significant drawbacks in its design activities. According to Suh's axiomatic design theory (ADT), design problems can be classified into three types: coupled design, decoupled design, and uncoupled design. In this paper, we further propose a decoupled design model for the decoupled design problem. A comparison of the two design models, MOCD and decoupled design, for several examples is given to support our finding and proposition.

Keywords - concurrent design; decoupled design; axiomatic design; mechanism.

I. INTRODUCTION

Design is an activity or process to generate structural features to meet requirements. The requirements can be classified into functional requirement (FR) and constraint requirement (CR). CR can be further classified into the equality constraint requirement (ECR) and the inequality constraint requirement (ICR). An example of FR is: 'a robot must pick an object with the weight of 5 g'; an example of ECR is: 'material must take aluminum'; and an example of ICR is: 'the cost of the system should be as low as possible or not more than $500'. The structural features are described by a so-called design parameter (DP). Therefore, design is to determine DPs to meet both FRs and CRs. It is easy to see that design is a trade-off among multiple FRs and CRs.

Concurrent design or engineering is a popular design paradigm since the 70s [Smith, 1997]. Concurrent design is originated from the idea that design and post-design activities, such as manufacturing, assembly and so on are considered at the design stage. In this way, the post-design activities become constraints to the design. Such a concurrent design may also be called design for manufacture or design for X [Boothroyd and Dewhurst, 1994]. In the late 90s, Zhang et al. [1999] extended design for X to design for control (DFC), suggesting that the design of mechanical structures and design of controllers are considered in such a way that controllability becomes a constraint to mechanical structure design. The basic idea of the DFC is that the mechanical structure is designed to have a simple dynamics so that controller design can be facilitated to achieve the overall performance of the whole system.

In the domain of designing a mechatronic mechanism or mechanism that is driven a servomotor, Yan and Yan [2009] presented a concurrent design procedure. The mechanism is supposed to fulfill a function, say \( F_d \) (d: desired), i.e. the functional requirement is \( F_d \). The mechanism should have as little shaking force (SF) and shaking moment (SM) as possible; i.e., the constraint requirement is the minimization of shaking force and shaking moment. The design model was expressed by [adapt from Yan and Yan, 2009]

\[
\begin{align*}
\text{Min} & \quad w_1 \times SF + w_2 \times SM \quad (1) \\
\text{Subject to:} & \quad F_a = F_d \quad (2)
\end{align*}
\]

where SF: shaking force; SM: shaking moment; \( F_a \): actual function; and \( F_d \): desired function. Further, the model can be converted to the unconstraint optimization problem by merging equations (1) and (2), i.e.

\[
\begin{align*}
\text{Min} & \quad w_1 \times SF + w_2 \times SM + w_3 \times |F_a - F_d| \quad (3)
\end{align*}
\]

In the above equation, \( w_i \) is a weight which represents the importance of a particular design goal. The above design model may be called multi-objective optimization concurrent design (MOCD) model. The question is: is the MOCD always the best? In this paper, we propose a proposition that the MOCD model is only suitable to the "coupled" design problem but not to "decoupled" nor to "uncoupled" design problem [Suh, 1990]. We shall later give the definition of types of design problems.

The quest of the effectiveness of concurrent design may date back to the paper of AitSahlia et al. [1995]. In their paper, they proved that concurrent engineering (CE) or design is not
the best for a design situation which involves high uncertainty. In particular, they took the cost and time as two criteria to evaluate a design and showed concurrent design in such uncertain situations may actually incur higher cost. They went on to propose a hybrid design process in that a sequential and a parallel designs are combined. However, in their work, only cost and time are considered as design goals. In our work, application specific design goals are considered. Further, they have not looked upon the feature of a design problem, e.g., decoupled design problem.

A more general study on whether concurrent design or engineering is always good was conducted by Valle and Vacquez-Bustelo [2009]. In their work, they have drawn some conclusion regarding the particular circumstance versus the benefit of CE. They went on to study a particular circumstance which is characterized by the type of new product development (i.e., the radical versus incremental) and the goals (time and cost). Unfortunately, they have not concerned the type of design or engineering problem in terms of the coupling or uncoupling between system and process parameters and requirements.

Alyaqout et al. [2011] proposed a sequential iterative design process for mechatronic systems, especially for two design goals: stability and robustness of the system. The proposed design process departs away from MOCD in order to reduce computation overhead. In traditional mechanism design, it is a common design practice to fully cancel shaking force first and then to minimize shaking moment and driving torque subject to the condition of full cancellation of shaking force [Arakelian and Dahan, 2001]. The nature of such a design process is not a concurrent design. There has been, however, no effort to generalize this design procedure in literature.

The objective of the present paper is to investigate the suitability of MOCD in the context of mechanism and machine design. In particular, we propose a decoupled design (DD) model or procedure for the decoupled design problem. We take a case study to compare the MOCD model and decoupled design model. In Section 2, we define three general types of design problems and discuss the relationship of MOCD with respect to these problems. In Section 3, we present a decoupled design model which best suits the decoupled design problem. In Section 4, we present a case study to show the decoupled design model is better than the MOCD model for the decoupled design problem. In Section 5, we conclude the paper.

II. MOCD VS DESIGN PROBLEMS

The nature of MOCD is that all design parameters are equally treated, which means that while they are being updated, they are considered to contribute to all design goals equally. However, the design parameters in equation (3) can be classified into two categories: (a) those affecting all the requirements (i.e., SF, SM and \( F_a - F_d \) in our case) – for example the length of a link component, and (b) those affecting a part of requirements (i.e., SF, SM in our case) – for example the mass and mass distribution. In this paper, the first category of design parameters is called kinematic parameter (Kin-P) and the second category of the design parameters is called dynamic parameter (Dyn-P).

It may be clear that Dyn-P only affects the objectives of the SF (and SM) but not \( F_a - F_d \), while Kin-P affects all the objectives. The design problem in our case is therefore called the decoupled design problem according to axiomatic design theory (ADT) [Suh, 1990] (Fig. 1a). There is thus a tension between MOCD problem and the decoupled design problem, as MOCD says that all design parameters equally contribute to all design requirements, but the decoupled design problem says that this is not true at all. In fact, from Fig. 1b, one can see that the coupled design problem meets MOCD. Further, from Fig. 1c, one can see that the uncoupled design problem does not meet MOCD either. It is straightforward to see that MOCD is not suitable to the uncoupled design problem. The uncoupled design problem should be tackled by a number of parallel design models with each achieving one objective only. Such a design model may be called the trivial concurrent design model.

In general, for a specific design problem, if a DP does not contribute to a FR or CR, to “tune” that DP to “meet” that FR or CR will compromise the DP’s contribution to meet other FRs or CRs that DP is supposed to meet. One may think that the adjustment of weights associated with objectives may be able to resolve the foregoing drawback with MOCD. However, this may turn out to be difficult, as the determination of weights is inherently a matter of empirical decision making. It is to be noted that a design problem may be partially coupled (see Fig. 1d). In this paper, we call both partially coupled and fully coupled design problems the coupled design problem. In the following, we shall propose a decoupled design model for the decoupled design problem.

![Figure 1. Types of design problems following the ADT [Suh, 1990]](image)

III. A MODEL FOR THE DECOUPLED DESIGN PROBLEM

Take a design problem containing two DPs and two FRs for illustration. According to the ADT [Suh, 1990], a decoupled design problem can be further represented by a “matrix” form, i.e.,

\[
\begin{bmatrix}
FR_1 \\
FR_2
\end{bmatrix}
= \begin{bmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2
\end{bmatrix}
\tag{4}
\]

where \( A_{ij} \) means the association between \( DP_i \) and \( FR_j \). In particular, \( A_{11} \) is defined as
\[ A_{ij} = \begin{cases} 1 & \text{if } DP_{i} \text{ and } FR_{i} \text{ are associated} \\ 0 & \text{if } DP_{i} \text{ and } FR_{i} \text{ are not associated} \end{cases} \quad (5) \]

A decoupled design model for the decoupled design problem (i.e., equation (4)), will take two steps.

Step 1: Optimize DP\(_{2}\) for FR\(_{2}\) with the relation of FR\(_{2}\) = \(f_{22}(DP_{2})\);

Step 2: Optimize DP\(_{1}\) for FR\(_{1}\) with the relation of FR\(_{1}\) = \(f_{11}^*(DP_{1}, DP_{2}^*)\) (where DP\(_{2}^*\) is the optimized DP\(_{2}\) through Step 1).

In the above design procedure, \(f_{ij}\) means a mapping from DP\(_{j}\) to DP\(_{i}\), and \(f_{ij}^*\) means a mapping from DP\(_{j}\) to DP\(_{i}\) while keeping other DPs unchanged. It is further noted that this decoupled design model shall be straightforwardly extended to a decoupled design problem with more than two DPs and two FRs. A general decoupled design problem can be represented by

\[
\begin{bmatrix}
FR_{1} \\
FR_{2} \\
\vdots \\
FR_{n}
\end{bmatrix} =
\begin{bmatrix}
A_{11} & A_{12} & \cdots & A_{1m} \\
A_{21} & A_{22} & \cdots & A_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
A_{m1} & A_{m2} & \cdots & A_{mm}
\end{bmatrix}
\begin{bmatrix}
DP_{1} \\
DP_{2} \\
\vdots \\
DP_{m}
\end{bmatrix} \quad (6)
\]

The general decoupled design procedure or model will then involve \(n\) design steps that are executed in sequence; namely, from the bottom of equation (6) toward the top. In the following, we shall apply both the MOCD and decoupled design models to several decoupled design problems to show drawbacks (in addition to computation overhead) with the MOCD model for these problems.

IV. CASE STUDY

A. Example design problem

We take a four-bar mechanism as an example. This mechanism is shown in Fig. 2, where the horizontal axis is along link 4 and the origin of the coordinate system is coincident with the pivot A. The dimensions of the mechanism are: \(l_1, l_2, l_3, l_4, l_5\) and \(\beta\). The mechanism is driven by a servomotor. The mechanism is supported to follow a predefined path which is composed of a set of positions at the end effect M. The primary goal of design is to determine the dimensions of the mechanism such that these positions can be reached. It is known that the maximal number of such positions is six according to mechanism design theory [Uicker et al., 2003]. It is common that while the primary goal is achieved, some secondary goals are desired; in particular, better dynamic performances (which are shaking moment, shaking force and driving torque considered in this paper) are often considered to be the secondary design goals.

The kinematic design goal is:

\[
\text{OF}(1) = \min \left( \frac{1}{6} \sum_{i=1}^{6} \left( M_{X_i} - M_{X_d} \right)^2 + \left( M_{Y_i} - M_{Y_d} \right)^2 \right) \quad (7)
\]

where: \(M_{X_i}\) and \(M_{Y_i}\) are the actual positions, \(M_{X_d}\) and \(M_{Y_d}\) are the desired positions. To maintain that link 1 is a crank we shall have the following constraint equation [Uicker et al., 2003].

\[
\text{Constraint} \left\{ \begin{array}{l}
c_1 = (l_{\text{min}} + l_{\text{max}}) - (l_p + l_q) < 0 \\
c_2 = l_1 - l_i < 0, \quad i = 2, 3, 4
\end{array} \right. \quad (8)
\]

The above discussion leads to the following design parameters: \(\{l_1, l_2, l_3, l_4, l_5, \beta\}\). These design parameters fall into the category of Kin-DP.

The dynamic design goal is:

\[
\text{OF}(2) = \min \{w_1 F_{SH} + w_2 T_{IN} + w_3 M_{SHA} + w_4 M_{SHD}\} \quad (9)
\]

where \(w_i\): weight (e.g., \(w_1 = w_2 = w_3 = w_4 = \frac{1}{4}\)); \(F_{SH}\): shaking force; \(T_{IN}\): driving torque; \(M_{SHA}\): moment with respect to point A; \(M_{SHD}\): moment with respect to D. The following constraint equations are established.

First, the motion is a periodical motion, which means that the angular velocity \(\omega(t)\) and angular acceleration \(\alpha(t)\) at the beginning and end of motion should be the same. We also consider that at the beginning and end, the angular displacement \(q(t)\) of the crank is zero. The following equation represents these constraints.

\[
\begin{align*}
\omega(1) - \omega(0) &= 0 \\
\alpha(1) - \alpha(0) &= 0 \\
q(1) &= 0 \\
q(0) &= 0
\end{align*}
\]

(10)
Second, there is design knowledge for the complete force balancing of the four-bar mechanism, which is represented by the following equation.

\[
\begin{align*}
\begin{cases}
m_1r_1 &= m_2r_2' + \frac{l_1}{l_2} \\
m_3r_3 &= m_2r_2' + \frac{l_3}{l_2} \\
\end{cases} \\
\theta_1 &= \theta_2' \\
\theta_3 &= \pi + \theta_2
\end{align*}
\tag{11}
\]

In the above equation, the definition of \(m_i, r_i, \theta_i\) can be found from Fig. 3. Further, denote \(m^*\) for an added mass and \(r^*\) for the location of the added mass, and denote \(m^0\) for an initial mass and \(r^0\) for the location of the initial mass. We will have the following equations which describe the relationship between initial masses and their distribution, added masses and their distribution, and final masses and their distribution, i.e.

\[
\begin{align*}
m_i'r_i e^{i\theta_i} &= m_i'r_i^* e^{i\theta_i^*} + m_i'^0 r_i^0 e^{i\theta_i^0} \\
m_i'r_i \left( (m_i'^0 r_i^0)^2 + (m_i'r_i^*)^2 - 2m_i'^0 r_i^0 m_i'r_i^* \cos(\theta_i^* - \theta_i^0) \right) \\
\theta_i &= \arctan\left( \frac{m_i'^0 r_i^0 \sin\theta_i^0 + m_i'r_i^* \sin\theta_i^*}{m_i'^0 r_i^0 \cos\theta_i^0 + m_i'r_i^* \cos\theta_i^*} \right) \\
m_i &= m_i' + m_i'^0 \\
l_i &= l_i^0 + m_i'u_i^2 + m_i'^0 u_i^2 \tag{15}
\end{align*}
\]

In equation (16), \(l_i(l_i^0)\): final (initial) moment of inertia of component \(i\). That the item in the root square in equation (13) must be greater than zero leads to the following equation.

\[
2m_i'^0 r_i^0 m_i'r_i^* \cos(\theta_i^* - \theta_i^0) - (m_i'^0 r_i^0)^2 - (m_i'r_i^*)^2 < 0
\tag{17}
\]

(i = 1, 2, 3)

Third, we shall constrain the location of the added mass, i.e., we impose the following constraint:

\[
\begin{align*}
r_i^* - 2l_1 &< 0 \\
r_i^* - 2l_2 &< 0 \\
r_i^* - 2l_3 &< 0
\end{align*}
\tag{18}
\]

The above discussion of the constraints leads to the following new design parameters, i.e.: \(\{m_i^*, r_i^*, \theta_i^*, m_i'^0, r_i^0, \theta_i^0\}\). These design parameters fall into the category of Dyn-DP. It is noted that Dyn-DP only affects the dynamic goal, while the Kin-DP will affect both the dynamic goals and kinematic goal.

Further, we consider that the motor is a speed-varying motor or servomotor. Therefore, the speed of the motor can be tailored to contribute to the design goals. The speed of the motor can be represented by a function of time \(t\). Assume that the function is a \(10^{th}\) order polynomial function. The speed of the motor is then represented by

\[
q_1 = a_0 + a_1 t + a_2 t^2 + \cdots + a_{10} t^{10} \quad t \in [0, 1] \tag{19}
\]

In a special case, the speed of the motor is a constant, which is denoted by \(\omega_{CV}\). It is noted that the parameters \(\{a_i\}\) and \(\omega_{CV}\) fall into the category of Kin-DP (i.e., they can affect both the kinematic goal and dynamic goal).

### B. Results and discussion

Suppose that the six required positions of \(M\) are: \((0.103, 0.220), (0.072, 0.242), (-0.004, 0.231), (-0.082, 0.149), (-0.091, 0.100)\) and \((0.36, 0.090)\) for the mechanism of Fig. 2. The original design parameters of the mechanism are given in Table I. The design problem is to achieve the goals or requirements of (a) reducing or canceling shaking force, (b) reducing or canceling shaking moment, (c) reducing or canceling driving torque, and (d) following six prescribed positions at the end-effector (M). In the following, MOCD and DD are applied to this design problem, respectively, and then compared.

#### TABLE I. THE DESIGN PARAMETERS OF THE ORIGINAL MECHANISM

<table>
<thead>
<tr>
<th>parameters</th>
<th>(l_1(m))</th>
<th>(l_2(m))</th>
<th>(l_3(m))</th>
<th>(l_4(m))</th>
<th>(l_5(m))</th>
<th>(\beta(\text{rad}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>1.05</td>
</tr>
</tbody>
</table>

With MOCD, we in particular take Equations (8), (10), (11), and (18) along with the equation below

\[
\text{OF} = w_1 \text{OF}(1) + w_2 \text{OF}(2) \tag{20}
\]

where \(\text{OF}(1)\) takes Equation (7) and \(\text{OF}(2)\) takes Equation (9) with \(w_4 = w_5 = \frac{1}{2}\). Further, in \(\text{OF}(2)\) – see Equation (9), all the weights take \(\frac{1}{4}\). Design parameters are \(\{l_1, l_2, l_3, l_4, q_1, q_2, q_3, q_4, q_5, q_6\} \) .

The result of the design is shown in Table II. In Fig. 4, \(\epsilon_p\) is the error between the required positions and the actual position of M, namely the result of the optimal objective OF(1). Fig. 4 and Fig. 5 show the performance of the mechanism before and after the design; in particular Fig. 4 for the kinematic motion performance and Fig. 5 for the dynamic performance. From Fig. 5 it can be seen that all the dynamic design goals or requirements (i.e., shaking force, shaking moment, and driving torque) are improved but shaking force is not completely cancelled. From Fig. 4 it can be seen that the prescribed positions are approximately reached with an accumulated error being 8.3725e-006 m.

#### TABLE II. THE RESULT OF THE DESIGN WITH MOCD

<table>
<thead>
<tr>
<th>Optimal Variable</th>
<th>Initial Values</th>
<th>Optimal Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>(l_1(m))</td>
<td>0.10</td>
<td>0.1029</td>
</tr>
</tbody>
</table>
With (DD), we take the following steps:

Step 1: Take the design parameters \( \{l_1, l_2, l_3, l_4, l_5, \beta \} \) to achieve the design goal (d) – i.e., the kinematic motion goal. The objective function takes Equation (7). The result of the design with DD is shown in Table III.

Step 2: Take the design parameters \( \{m'_1, r'_3, \theta'_3, m'_2, r'_2, \theta'_2, m'_3, r'_3, \theta'_3 \} \) to fully cancel shaking force. This means to determine design parameters to satisfy equation (11). It is noted that equation (11) has four equations. With the design parameters \( \{m'_1, r'_3, \theta'_3, m'_2, r'_2, \theta'_2, m'_3, r'_3, \theta'_3 \} \), there are five parameters that are free to be used for achieving other design goals. Denote the set of five parameters from the set \( \{m'_1, r'_3, \theta'_3, m'_2, r'_2, \theta'_2, m'_3, r'_3, \theta'_3 \} \) as \( \{DP^* \} \).

Step 3: Take design parameters \( \{DP^* \} \) and \( \{a_0, a_1, \cdots, a_{10} \} \) to minimize shaking moment and driving torque.

The implementation of Step (2) and Step (3) above results in the following optimization model: the objective function is \( OF = \min[w_1 T_{IN} + w_2 M_{SH}] \) (where \( w_1 = w_2 = \frac{1}{2} \)); \( T_{IN} \): driving torque; \( M_{SH} \): shaking moment); design parameters are \( \{m'_1, r'_3, \theta'_3, m'_2, r'_2, \theta'_2, m'_3, r'_3, \theta'_3 \} \) with the design parameters \( \{r'_3, \theta'_3, m'_3, \theta'_3 \} \) being found from equations (11), (12) to (16), which corresponds to full cancelation of shaking force, the constraints are equations (10), (17), (18); the result of the decoupled design procedure is shown in Table III. Fig. 6 and Fig. 7 show the kinematic motion performance and dynamic performance of the mechanism before and after the design with DD, respectively.

### Table III: The Result of the Design with DD

<table>
<thead>
<tr>
<th>Optimal Variable</th>
<th>Initial Values</th>
<th>Optimal Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_1 (m) )</td>
<td>-</td>
<td>0.1030</td>
</tr>
<tr>
<td>( l_2 (m) )</td>
<td>-</td>
<td>0.3040</td>
</tr>
<tr>
<td>( l_3 (m) )</td>
<td>-</td>
<td>0.2410</td>
</tr>
<tr>
<td>( l_4 (m) )</td>
<td>-</td>
<td>0.2980</td>
</tr>
<tr>
<td>( l_5 (m) )</td>
<td>-</td>
<td>0.1500</td>
</tr>
<tr>
<td>( \beta (rad) )</td>
<td>-</td>
<td>0.7854</td>
</tr>
<tr>
<td>( m_1 (kg) )</td>
<td>0</td>
<td>0.2525</td>
</tr>
<tr>
<td>( m_2 (kg) )</td>
<td>0</td>
<td>2.3231</td>
</tr>
<tr>
<td>( m_3 (kg) )</td>
<td>0</td>
<td>-0.5001</td>
</tr>
<tr>
<td>( r'_3 (m) )</td>
<td>0</td>
<td>0.1500</td>
</tr>
<tr>
<td>( \theta'_2 (rad) )</td>
<td>0</td>
<td>3.1340</td>
</tr>
<tr>
<td>( a_0 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>0</td>
<td>6.2832</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>0</td>
<td>0.0014</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>0</td>
<td>0.0014</td>
</tr>
<tr>
<td>( a_4 )</td>
<td>0</td>
<td>-0.0031</td>
</tr>
<tr>
<td>( a_5 )</td>
<td>0</td>
<td>0.0021</td>
</tr>
<tr>
<td>( a_6 )</td>
<td>0</td>
<td>0.0009</td>
</tr>
<tr>
<td>( a_7 )</td>
<td>0</td>
<td>-0.0002</td>
</tr>
<tr>
<td>( a_8 )</td>
<td>0</td>
<td>0.0003</td>
</tr>
<tr>
<td>( a_9 )</td>
<td>0</td>
<td>-0.0001</td>
</tr>
<tr>
<td>( a_{10} )</td>
<td>0</td>
<td>0.0008</td>
</tr>
<tr>
<td>( e_p (m) )</td>
<td>-</td>
<td>8.3725e-006</td>
</tr>
</tbody>
</table>

**Figure 4.** The kinematic motion performance of the mechanism before and after the design with MOCD.

**Figure 5.** The dynamic performance of the mechanism before and after the design with MOCD.
Comparison of MOCD and DD leads to the following results: (1) From Fig. 7 and Fig. 5, it can be seen that the dynamic performance of the design with DD is better than that with MOCD; (2) From Fig. 6 and Fig. 4, it can be seen that the kinematic motion performance of the design with DD is better than that with MOCD.

In the following, we shall show how difficult would it be with MOCD in choosing weights. We revisit the problem with MOCD. Table IV shows different results of the error of the kinematic motion performance with four different weights. It is clear that when the higher weights are put to the kinematic goal, the kinematic error is reduced, which means that the kinematic goal is more satisfied. Since the weights are determined arbitrarily or determined without a clear understanding the design consequence, the result of the design with MOCD is of uncertainty.

TABLE IV. THE RESULTS OF THE ERROR WITH DIFFERENT WEIGHTS OF THE DESIGN WITH MOCD (CASE 2)

<table>
<thead>
<tr>
<th>weights</th>
<th>( w_1 = 0.1 )</th>
<th>( w_2 = 0.3 )</th>
<th>( w_3 = 0.5 )</th>
<th>( w_4 = 0.9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e_{kp}(m) )</td>
<td>8.5745e-004</td>
<td>4.8754e-005</td>
<td>8.3725e-006</td>
<td>5.3521e-010</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

In this paper, we argued that the conventional concurrent engineering approach to the design problem with multiple objectives and constraints may not be the best. Our study concludes: (1) the concurrent design (i.e., MOCD) model is only suitable to the design problem in which design goals and design parameters are coupled; (2) for the design problem, which is called decoupled design problem, a decoupled design model should be employed; and (3) for the design problem, which is called uncoupled design, a trivial concurrent design approach should be employed, in which a number of design models are employed to a number of design goals. On a general note, when a design is so-called modular design, the concurrent design model (i.e. MOCD) will have to be employed. This is because the design problem in this case is fully coupled; that is to say, a particular module will have effect to all design goals or requirements. This finding was first made by Bi and Zhang [2002].

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