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Abstract

1 Introduction

enterprise

enterprise-level product planning

engineering product development

V $\mathbf{T}^U$

$\mathbf{x}_{ent}$

$\mathbf{g}_{ent} \leq \mathbf{0}$ $\mathbf{h}_{ent} = \mathbf{0}$

$\mathbf{R},$

$\mathbf{g}$ $\mathbf{h}$

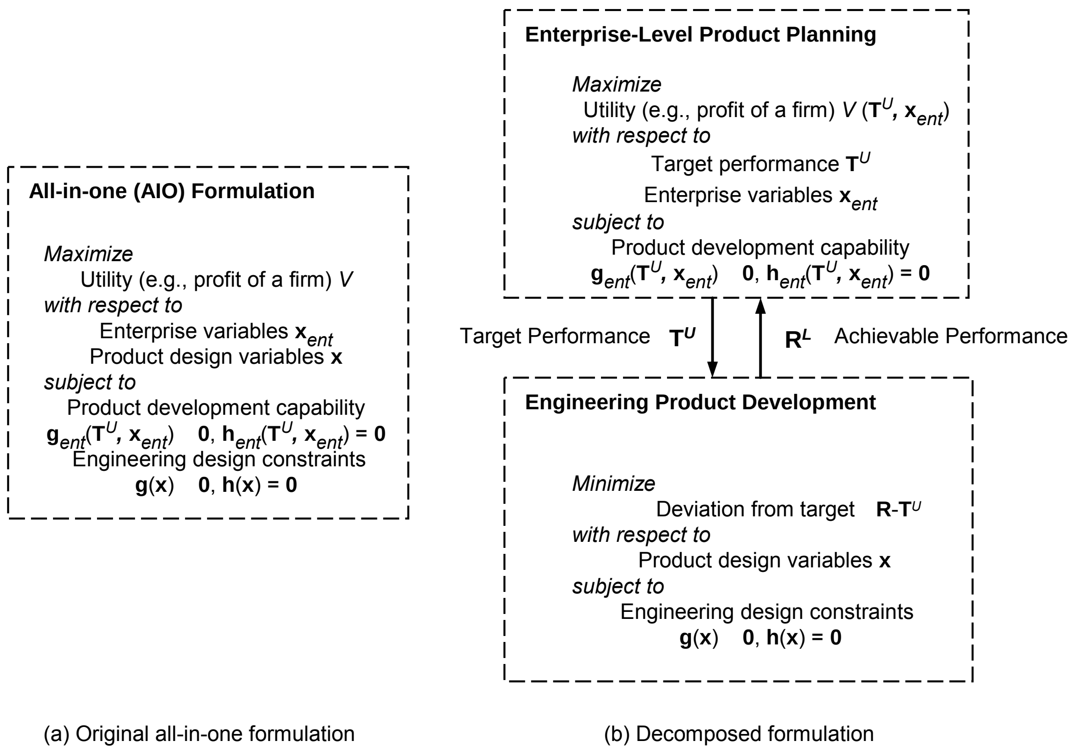


Figure 1. Interaction between enterprise product planning and engineering product development

2 Enterprise Product Planning and Engineering Product Development Model

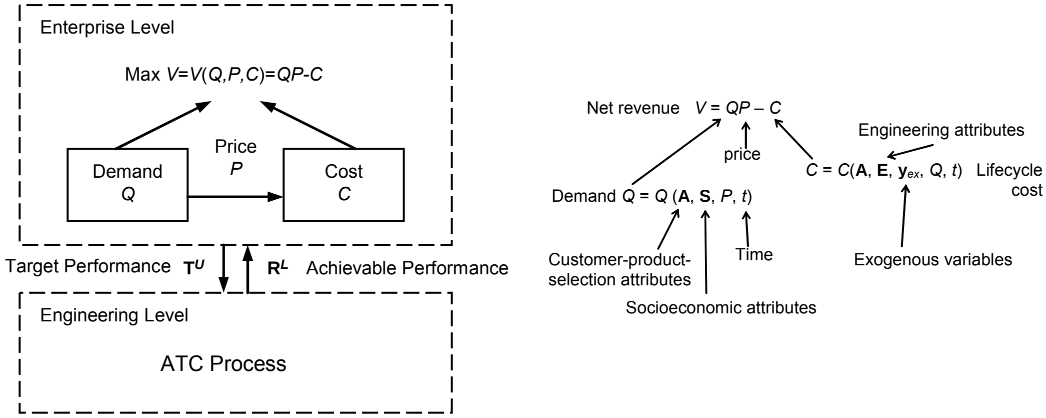


Figure 2. Bi-level enterprise decision flow and net revenue model.

Q

V

Q

$\mathbf{A}$ $\mathbf{S}$ P t

C

$\mathbf{A}$ $\mathbf{E}$

$\mathbf{y}_{ex}$ Q t $\mathbf{A}$

$\mathbf{E}$

$\mathbf{T}$ $\mathbf{A}$ $\mathbf{E}$

$\mathbf{A}$ $\mathbf{E}$

$Pr_n\ i$

n $i\ J$ n W

$$Pr_n\ i\ = \frac{e^{W_{in}}}{\sum_{j \in J} e^{W_{jn}}}$$

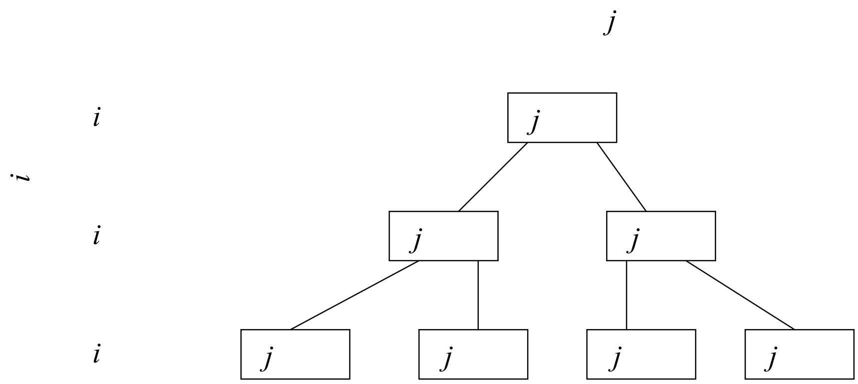


Figure 3. Decomposition example with three-level hierarchy

P_{ij} j^{th} i^{th}

$$\mathbf{R}_{ij} = \left[\mathbf{R}_{ij}\ \ \mathbf{R}_{ij}\right]^T = \mathbf{r}_{ij}(\mathbf{R}_{i+\ \ k}, \ldots, \mathbf{R}_{i+\ \ k_{c_{ij}}}, \mathbf{x}_{ij}\ \ \mathbf{y}_{ij})$$

$$\mathbf{x} = \ \mathbf{x}_{ij}\ \ \mathbf{y}_{ij}, \mathbf{y}_{i+\ \ k}, \ldots, \mathbf{y}_{i+\ \ k_{c_{ij}}}, \mathbf{R}_{i+\ \ k}, \ldots, \mathbf{y}_{i+\ \ k_{c_{ij}}}, \boldsymbol{\varepsilon}^{\mathbf{R}}_{ij}\ \ \boldsymbol{\varepsilon}^{\mathbf{y}}_{ij}\ \ ^T$$ $\mathbf{x}_{ij}$

$\mathbf{R}_{ij}$ $\mathbf{R}_{ij}$

$\boldsymbol{\varepsilon}^{\mathbf{R}}_{ij}$ $\boldsymbol{\varepsilon}^{\mathbf{y}}_{ij}$

$\cdot)^U$ $\cdot)^L$

$\mathbf{T}$ $\mathbf{g}_{ij}$ $\mathbf{h}_{ij}$

$\mathbf{w}$

$$P_{ij} \quad \mathbf{w}_{ij}^{\mathbf{R}} \left\| \mathbf{R}_{ij} - \mathbf{T}_{ij} \right\| + \mathbf{w}_{ij}^{\mathbf{R}} \left\| \mathbf{R}_{ij} - \mathbf{R}_{ij}^{U} \right\| + \mathbf{w}_{ij}^{\mathbf{y}} \left\| \mathbf{y}_{ij} - \mathbf{y}_{ij}^{U} \right\| + \boldsymbol{\varepsilon}_{ij}^{\mathbf{R}} + \boldsymbol{\varepsilon}_{ij}^{\mathbf{y}}$$

$$\sum_{k \in C_{ij}} \left\| \mathbf{R}_{i+\ \ k} - \mathbf{R}_{i+\ \ k}^{L} \right\| \leq \boldsymbol{\varepsilon}_{ij}^{\mathbf{R}}$$

$$\sum_{k \in C_{ij}} \left\| \mathbf{y}_{i+\ \ k} - \mathbf{y}_{i+\ \ k}^{L} \right\| \leq \boldsymbol{\varepsilon}_{ij}^{\mathbf{y}}$$

$$\mathbf{g}_{ij} \quad \mathbf{R}_{ij}, \mathbf{x}_{ij} \quad \mathbf{y}_{ij}) \leq \mathbf{0}$$

$$h_{ij} \quad \mathbf{R}_{ij}, \mathbf{x}_{ij} \quad \mathbf{y}_{ij}) = \mathbf{0}$$

3 Multilevel Enterprise and Engineering Problem Formulation and Solution Algorithm

$$P_{ent} \quad_{\mathbf{T}\ \mathbf{x}_{ent}} \quad V \ \mathbf{T} \ \mathbf{x}_{ent}$$

V $\mathbf{T}$

$\mathbf{x}_{ent}$

$\mathbf{T}$ V

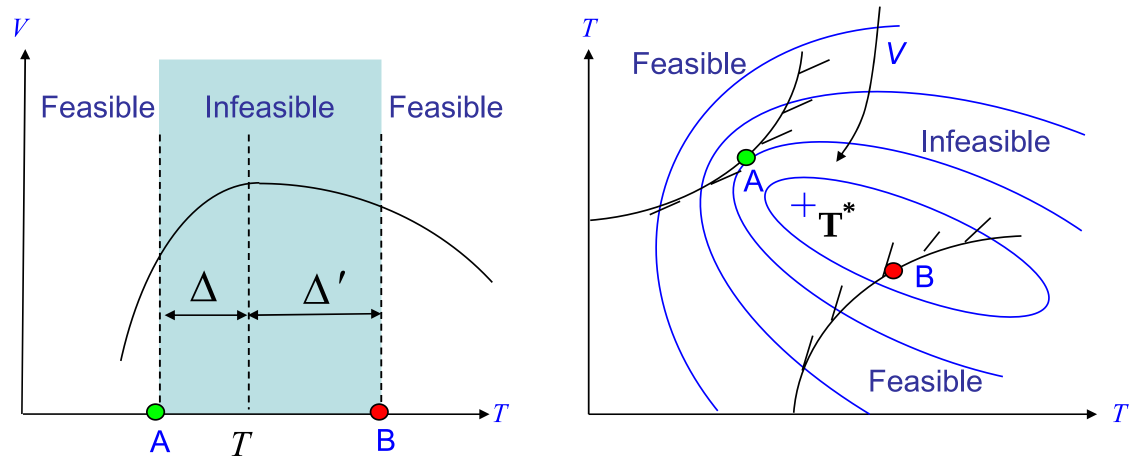
$\mathbf{R}^L$

3.1 Introducing a new constraint in the enterprise-level problem

C_{aux}

$\mathbf{R}^L$

$$C_{aux} \quad \left\| \mathbf{T} - \mathbf{R}^{L} \quad \right\| \geq \Delta = \left\| \mathbf{T} \quad - \mathbf{R}^{L} \quad \right\|$$



(a) One-dimensional case (b) Two-dimensional case

Figure 4. Utilities with engineering feasible domain imposed. Points A and B are both engineering local optima with the minimum deviation from the target. The deviation for the point A is smaller, but the corresponding utility is not higher than that of point B.

$\mathbf{T}$

P'_{ent} $\mathbf{T}'$

$\mathbf{T}'$

$$P'_{ent} \quad {}_{\mathbf{T}\ \mathbf{x}_{ent}} \quad V\ \mathbf{T}\ \mathbf{x}_{ent}$$

$$C_{aux}\ \ \left\|\mathbf{T}-\mathbf{R}^{L}\ \right\| \geq \Delta = \left\|\mathbf{T}\ \ -\mathbf{R}^{L}\ \right\|$$

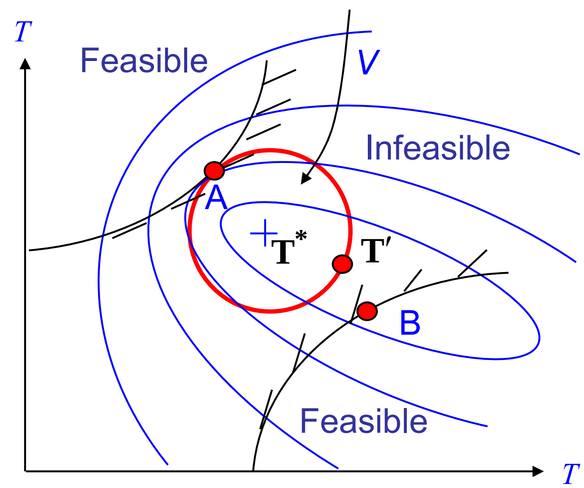
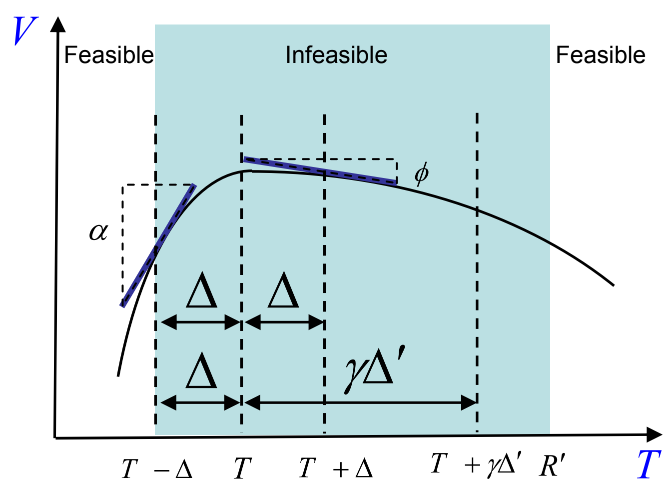


Figure 5. A circular constraint imposes a new target $\mathbf{T}'$ for the engineering problem.



$$\Delta' = \left|\frac{\alpha}{\phi}\right|\Delta$$

Figure 6. Updating the radius Δ in the additional constraint in the modified enterprise problem: the slope is considered to set the radius of the constraint (Eq. 4)

3.2 Utilization of the slope information

$T - \Delta$

$T + \Delta$

$T + \Delta$

$T - \Delta$

$T - \Delta$

$\alpha,$

$T + \Delta$

$\phi,$

$T - \Delta$ $|\phi| \le |\alpha|$ Δ'

$$\Delta' = \left|\frac{\alpha}{\phi}\right|\Delta$$

$T \quad + \gamma\Delta'$

R' γ

$\left|\frac{\phi}{\alpha}\right| < \gamma \le$ $\gamma = \left|\frac{\phi}{\alpha}\right|$

Δ $\gamma =$ Δ' γ

$\left|\frac{\phi}{\alpha}\right| < \gamma \le$

γ

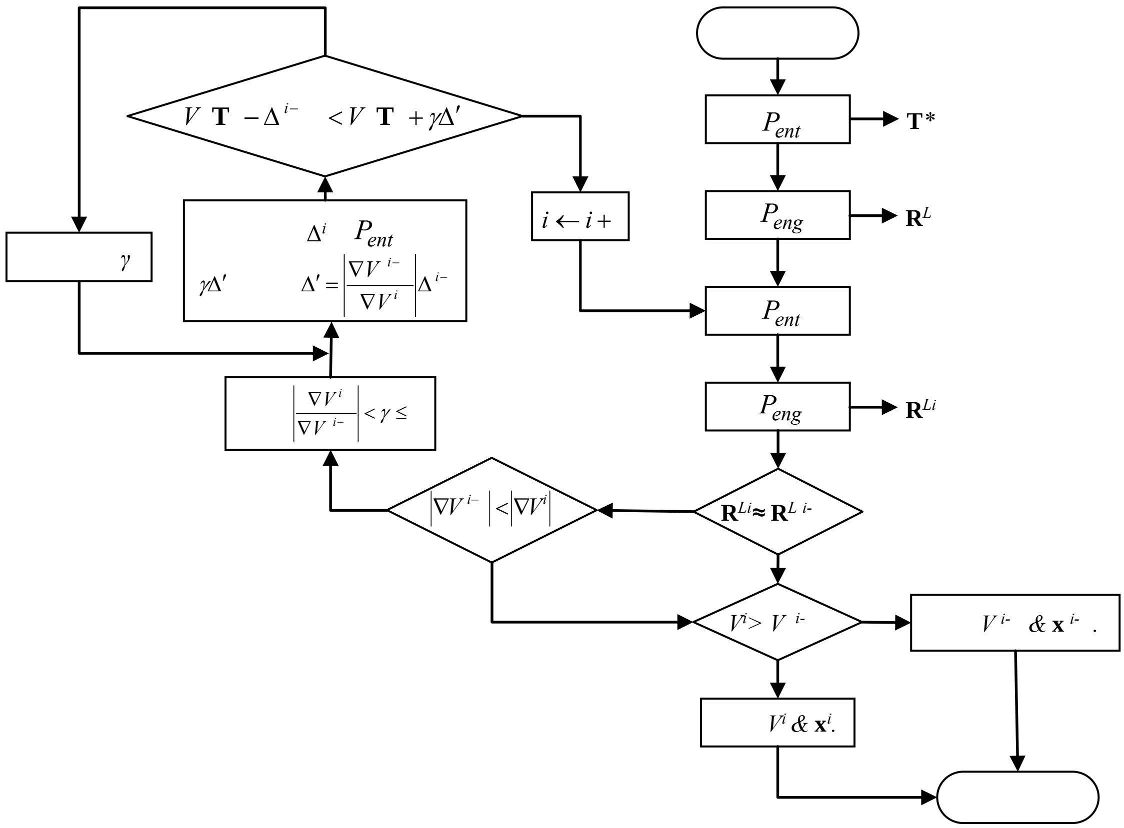


Figure 7. Solution algorithm

explores

Algorithm

1. Start with $\mathbf{x}$.

2. Solve the original enterprise problem P_{ent} *and find the utopia target* $\mathbf{T}$.

3. Solve the engineering problem P_{eng} *and obtain the response* $\mathbf{R}^{L}$ *with the minimum deviation from the target* $\mathbf{T}$.

4. Add an additional constraint C_{aux} *in the enterprise problem and find a new target* $\mathbf{T}^{i}$ *by solving the modified enterprise problem* P'_{ent} .

5. Solve the engineering problem and obtain the response $\mathbf{R}^{Li}$ *with the minimum deviation from the target* $\mathbf{T}^{i}$.

6. If $\mathbf{R}^{Li} \approx \mathbf{R}^{L\ i-}$ $\left|\nabla V^{\ i-}\ \right| < \left|\nabla V^{i}\right|$, *increase* Δ *in* C_{aux} *in* P'_{ent} *to* $\Delta^{i} = \gamma\left|\dfrac{\nabla V^{\ i-}}{\nabla V^{i}}\right|\Delta^{i-}$ *where* $\left|\dfrac{\nabla V^{i}}{\nabla V^{\ i-}}\right| \le \gamma \le\ $.

   6.1. If $V\ \ T\ \ -\Delta^{i-}\ \ < V\ \ T\ \ +\Delta^{i}$ *go to step 4 and solve* P'_{ent}

   6.2. Otherwise, decrease γ until it satisfies $V\ \ T\ \ -\Delta^{i-}\ \ < V\ \ T\ \ +\Delta^{i}$.

7. If $\mathbf{R}^{Li} \approx \mathbf{R}^{L\ i-}$ $\left|\nabla V^{\ i-}\ \right| \ge \left|\nabla V^{i}\right|$, *compare the current enterprise utility value to the previous one and accept the current design if improved, or accept the previous design.*

8. End.

4 Demonstration and Verifications

4.1 Analytical Examples

4.1.1 Utility with Single Optimum

P_s P_{sub} P_{sub}

T T

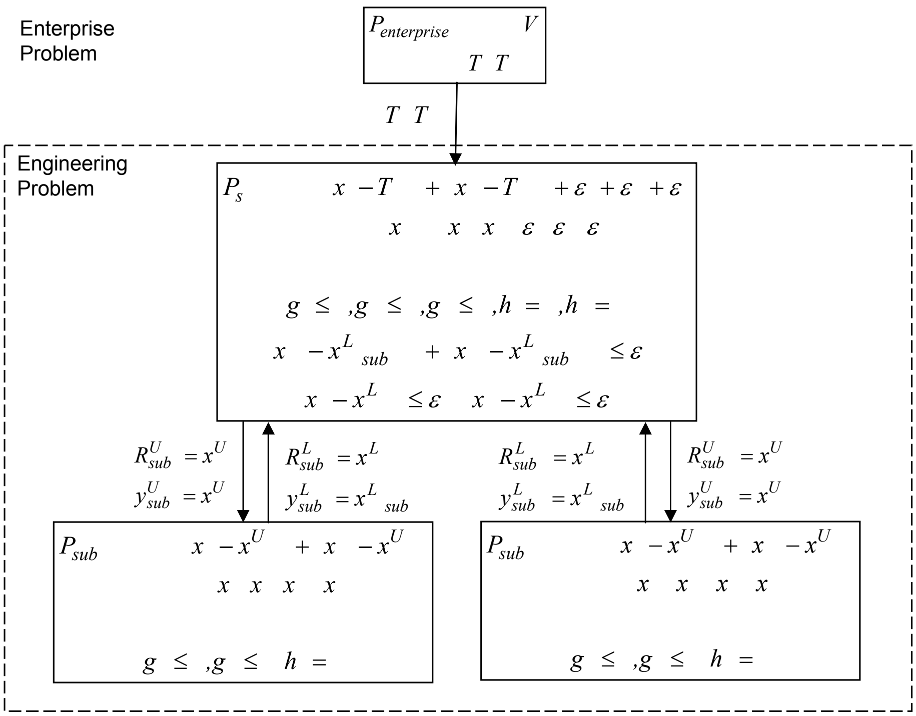
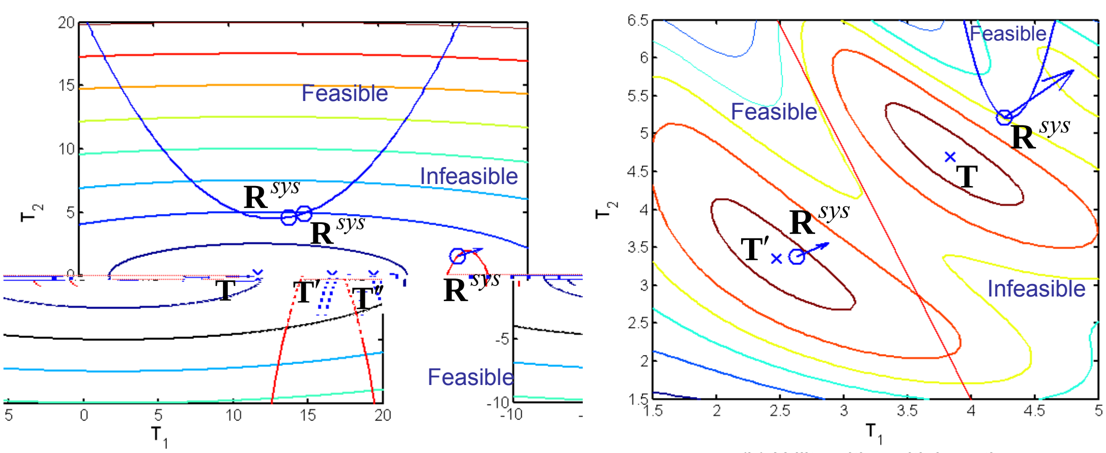


Figure 8. Decomposed problem hierarchy following analytical target cascading.



(a) Utility with single optimum

(b) Utility with multiple optima

Figure 9. Disconnected feasible domains are mapped over the utility space. The arrows represent the gradient.

T T

$\mathbf{T}$ =

$\mathbf{R}^{sys}$ =

$\mathbf{R}^{sys}$

$\mathbf{T}'$ $\mathbf{R}^{sys}$

$\mathbf{R}^{sys}$

$\Delta' = \gamma \left| \frac{\nabla V^{i-}}{\nabla V^{i}} \right| \Delta$ $\left| \frac{\nabla V^{i}}{\nabla V^{i-}} \right| \leq \gamma \leq$ $\mathbf{T}''$

$\mathbf{R}^{sys}$

$\mathbf{R}^{sys}$

x x $\ldots$ x =

Table 1 Iteration History: Utility with single optimum

	T	T	

4.1.2 Utility with Multiple Local Optima

$$P_{ent}$$

$$_{T\ T} \quad V = \quad + \quad T \ - T \quad + \quad - T$$

$$+ \quad - T \quad + \quad T \quad T\,T$$

$$T \ \ T$$

$$P_{eng} \quad x \; x \; \ldots \; x \qquad x \; - T \quad + \; x \; - T$$

$$g \;=\; x^{-} \;+ x \quad x \;-\; \leq \qquad g \;=\; x \;+ x^{-} \quad x \;-\; \leq$$

$$g \;=\; x \;+ x \quad x \;-\; \leq \qquad g \;=\; x^{-} \;+ x \quad x \;-\; \leq$$

$$g \;=\; x \;+ x^{-} \quad x \;-\; \leq \qquad g \;=\; x \;+ x \quad x \;-\; \leq$$

$$g \;= - \quad x \; - \qquad + \quad - x \quad - \quad x \; - \qquad + \; - x \quad \leq$$

$$h \; = x \; - x \; - x^{-} \; - x \; = \qquad h \; = x \; - x \; - x \; - x \; =$$

$$h \; = x \; - x \; - x^{-} \; - x^{-} \; - x \; = \qquad h \; = x \; - x \; - x \; - x \; - x \; =$$

$$- \quad \leq x \quad x \quad \ldots \; x \quad \leq$$

g

$\mathbf{T} \;=$

$\mathbf{R}^{sys} \;=$ $\mathbf{R}^{sys}$

$\mathbf{T}'$

$\mathbf{R}^{sys}$

$\mathbf{R}^{sys}$

$x \quad x \quad \ldots \; x \quad =$

Table 2 Iteration History: Utility with Multiple Optima

	T	*T*

4.2 Enterprise–Driven Multilevel Vehicle Suspension Design

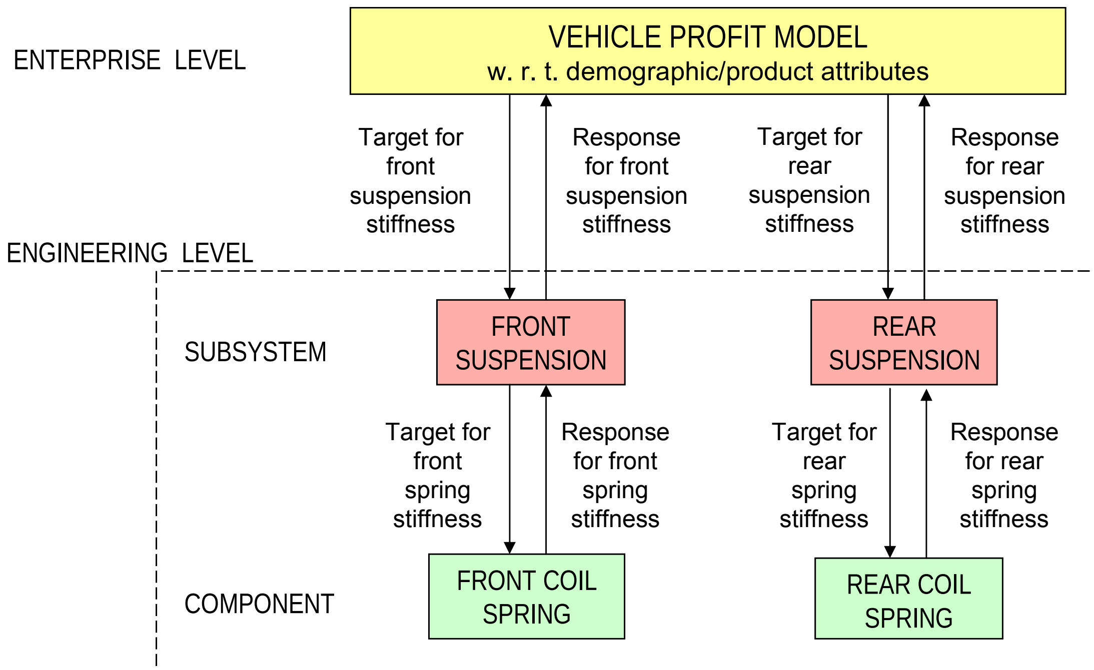


Figure 10. Schematic of vehicle profit and suspension design model

4.2.1 Medium Size Vehicle Demand Model

U_{in}

W_{in} ε_{in}

$$U_{in} = W_{in} + \varepsilon_{in}$$

$\mathbf{A}$ $\mathbf{E}$

$\mathbf{S}$ P β

β

n n^{th}

i i^{th}

W

β

$$W_{in} = f \;\; \mathbf{A}_i \;\; \mathbf{E}_i \;\; P_i \;\; \mathbf{S}_n \;\; \beta_n$$

Q

Table 3 Results of Demand Model Estimation

	β	

P C_{susp} C

$$\Pi = Q\ \mathbf{A,E,S}\ \times\ P - C_{susp} - C$$

$P =$ $C\ =$ a_f a_r $k_{sf}\ =$

$k_{sr}\ =$

$$\Delta\Pi = Q\ k_{sf}\ \ k_{sr}\ \times\ \ -a_f k_{sf} - a_r k_{sr}\ \ P - C$$
$$-Q\ k_{sf}\ \ k_{sr}\ \ \times\ \ -a_f k_{sf}\ \ -a_r k_{sr}\ \ P - C$$

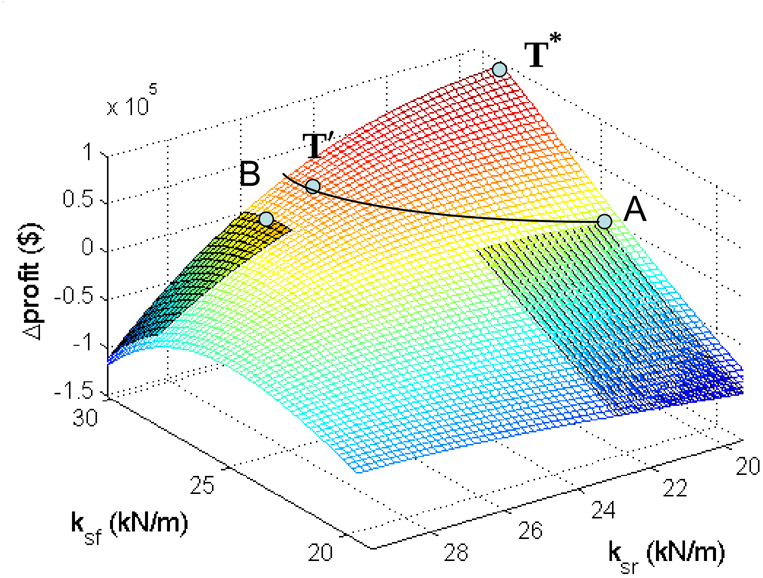


Figure 11. Vehicle profit model: profit change with respect to suspension stiffness changes. The shaded

areas represent feasible suspension design domain. The baseline vehicle suspension stiffnesses are k_{sf} = [kN/m] and k_{sr} = [kN/m]. The solid curve connecting A and T′ indicates the geometric distance constraint.

4.2.2 Implementation of Proposed Algorithm

Table 4 Iteration History: Maximizing Profit with Vehicle Suspension Design Change

	k_{sf}	k_{sr}		k_{sf}	k_{sr}	

T =

A =

T′ =

B =

5 Conclusions

Appendix

Table 5 Front Suspension Design

Table 6 Rear Suspension Design

Table 7 Front Coil Spring Design

Table 8 Rear Coil Spring Design

Acknowledgment

References

Proceedings of DETC 2001 ASME Design Engineering Technical Conference

Proceedings of DETC 2002 ASME Design Engineering Technical Conference

Proceedings of DETC 2000 ASME Design Engineering Technical Conference,

Transactions of ASME: Journal of Mechanical Design

Transactions of ASME: Journal of Mechanical Design *Proceedings of the 2003 ASME Design Automation Conference*

Transactions of ASME: Journal of Mechanical Design

Journal of Product Innovation

Management: Special Issue on Design and Marketing in New Product Development

AIAA Journal
Discrete Choice Analysis

Systems Engineering: An Approach to Information-Based Design

Journal of Mechanical Design

Proceedings of DETC
2004 ASME Design Engineering Technical Conference

Concurrent Engineering: Research and Applications

Advances in Design Automation

Engineering Optimization

AIAA Journal

Engineering Optimization
Annals of Discrete Mathematics

Industrial and Engineering Chemistry Research
Disjunctive approaches for solving general mixed-integer linear programs

Proceedings of the 12th International Conference on Engineering Design
Target Cascading in Optimal System Design

Transactions of ASME: Journal of Mechanical Design

Transactions of ASME: Journal of Mechanical Design

Collaborative optimization: An architecture for large-scale distributed design

Structural Optimization

Proceedings of the 38th AIAA/ASME/ASCE/HS/ASC, Structures, Structural Dynamics and Materials Conference

Journal of Marketing

Handbook of Transport Modeling

Transactions of ASME: Journal of Mechanical Design

Proceedings of IFORS 2005

Proceedings of 6th World Congress of Structural and Multidisciplinary Optimization

Ward's automotive yearbook

Stata Programming Reference Manual