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**Article**

# Product Design of Balance Bikes Using Decision-Making Trial and Evaluation Laboratory (DEMATEL)

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**Abstract:** By analyzing the relationship between components of a product, the decision-making trial and evaluation laboratory (DEMATEL) was used to visualize the structure of intricate causal relationships of factors that affect purchase decisions for Balance Bikes. Cluster analysis was employed to visualize the structural relationship. We took three Balance Bike designs to apply DEMATEL in their design development and compared DEMATEL results with the results of the questionnaire survey and interviews. The result showed that DEMATEL can be applied to product design and development. For Balance Bike design, respondents valued aesthetics and delivery more than other indicators including practicality, productivity, functionality, and operability.

**Keywords:** Product development; Product design; DEMATEL; Balance Bike

## 1. Introduction

Energy saving and environmental protection are emphasized in the sports and leisure industry nowadays. Balance Bikes are one of the most favorable products for sports and leisure. Balance Bikes have been developed over decades and become more popular than before as there is no need to use fuel or electricity to ride on them. In addition, they do not cause environmental pollution and traffic congestion. As the speed of a Balance Bike is not fast, there is not much concern about accidents on the road and no special infrastructure is needed for riding on a Balance Bike. Using Balance Bikes for transportation can save social resources, and is suitable for leisure activities, which is in line with modern living needs. The design of the Balance Bike is diverse but most Balance Bikes are designed for children. Therefore, there has not been a strong demand for the functionality of Balance Bikes, and consumers care more about the price and appearance.

To improve the functionality of a product, the psychological aspects of consumers must be considered. Hu and Liao (2010) and Sun et a;l. (2009) explored the life and consumption styles of consumers aged 18 to 38 years old and found that consumers chose bicycles based on their perceptual evaluation. Wang (2002) used a vocabulary-based questionnaire to understand how the shapes of bicycle frames (top tube, head tube, down tube, seat tube, and seat stays). Based on perception, they described the shape of the bicycle using qualitative analyses and different sensory imagery and applied the result to product design. Then, they constructed a sample product based on the design principles and investigated the effect of the tube diameter on the shape of the bicycle. In the research, adjectives were used to evaluate the shape of the frame.

Tseng proposed a hybrid fuzzy set theory and analytical network process (ANP) to examine two hierarchical structures for green supply chain management (Tseng et al, 2014). Yeh and Huang (2014) used the decision-making experimentation and evaluation laboratory (DEMATEL) and ANP to determine the relative weights of dimensions and criteria. They found that safety and quality, and environment and ecology were two main groups of factors that were important in the development of wind power plants and the public's understanding. Hsu adopted DEMATEL to simplify and visualize the interrelationships between the criteria for decision-making. Chang et al. (2011) adopted DEMATEL to analyze and predict suppliers in the electronics industry and found that the key factor of cargo delivery impacted the choice of suppliers for effective supply chain management. DEMATEL was also used to explore the causal relationship between fine dining and service quality for strategic planning and resource allocation in the catering industry to enhance the service quality of hotels (Cheng et al., 2012). With the concept of modularity, diversified design concepts and a variety of proposals were developed for different needs to save manufacturing costs by sharing components of various products (Hsiao et al., 2013).

The relationship between components can be explored based on previous models. However, the models could not find appropriate product groups for market segments. To do this, it is necessary to optimize weight distribution between generic and standalone components. Currently, numerous new products are developed based on customer needs. The relationship between diverse components of products and diverse consumer groups influences each other in each market segmentation. Thus, it is mandated to study the network relationship between them to establish the effective distribution of the product.

## 2. Methods

### *2.1. Cluster Analysis*

Cluster analysis is used to classify objects into clusters using pre-processed data and their internal distribution. Clusters are considered as a set of objects since similar objects belong to the same group. Based on the assigned attributes, the data are categorized to have homogeneity (or similarity). Cluster analysis is based on the degree of variable density. Each object is considered as a point in an n-dimensional space (n = number of variables), and the distance or the degree of similarity between objects in the space is calculated. In this study, the subgroups of objects were defined as consumers in the market

### *2.2. DEMATEL*

When the interactions between the evaluation criteria are complex and not fully explained by the analytical hierarchical process (AHP), ANP is used to solve the problem of internal dependencies and external feedback of the clusters. Since ANP defines each facet or cluster of the same weight, the degree of influence between clusters is not always the same. In other words, ANP ignores the importance of the proportion of weights among clusters. DEMATEL converts the degree of influence of complex structures or inter-cluster interactions into a causal relationship and establishes the relationship structure of the ANP model using the weights of inter-cluster interactions. In this way, the problem can be studied more objectively and scientifically. DEMATEL was developed by the Battelle Memorial Institute of Geneva between 1972 and 1976 for the Science and Human Affairs Program. DEMATEL is used to solve complex and entangled problems, whereby DEMATEL enhances the understanding of the particular problem and identifies feasible solutions in a hierarchical structure (Tzeng et al., 2007). The most important feature of DEMATEL is to illustrate the interrelationships between factors or clusters and to derive essential criteria for effective representation. DEMATEL has been applied in marketing strategies, control systems, security issues, global managers, and capacity development for decision-making. DEMATEL is a method to examine mutual influences or self-feedbacks among factors and construct a network diagram of the relationship between the criteria. and Tzeng et al. (2007) used DEMATEL to identify feasible solutions for problems using hierarchical structures. The process of DEMATEL is described as follows.

**Step 1: Impact Matrix**

A criterion-based pairwise decision-making is used to assess each respondent's perception of the degree of influence between indicators. Respondents are asked about their degree of influence, and the results are assessed on an influence scale of "no influence at all (0)", "slight influence (1)", "average influence (2)", "high influence (3)", and "very high influence (4)". A direct impact matrix is obtained from the responses of the respondents (Eq. (1)).

$$A = \left[a_{ij}\right]_{mxn} \tag{1}$$

**Step 2: Normalized Impact Matrix**

The impact matrix is normalized using Eqs. (2) and (3) to obtain the normalized impact matrix $D = \left[d_{ij}\right]_{mxn}$. The diagonal of the matrix is 0.

$$D = kA \tag{2}$$

$$k = \min\left\{1/\max_i \sum_{j=1}^{n} a_{ij}, 1/\max_j \sum_{i=1}^{n} a_{ij}\right\} \tag{3}$$

$$i, j \in \{1, 2, ..., n\}$$

**Step 3: Relationship Matrix**

After obtaining the normalized impact matrix, Eq. (4) is used to calculate the total influence matrix $T$ of the constructed network relationship graph, where $I$ is the unit matrix.

$$\boldsymbol{T} = \boldsymbol{D} + \boldsymbol{D}^2 + \boldsymbol{D}^3 + ... + \boldsymbol{D}^k = \boldsymbol{D}(\boldsymbol{I} + \boldsymbol{D} + \boldsymbol{D}^2 + ... + \boldsymbol{D}^{k-1})[(\boldsymbol{I} - \boldsymbol{D})(\boldsymbol{I} - \boldsymbol{D})^{-1}] = \boldsymbol{D}(\boldsymbol{I} - \boldsymbol{D}^k)(\boldsymbol{I} - \boldsymbol{D})^{-1} \tag{4}$$

$$\boldsymbol{T} = \boldsymbol{D}(\boldsymbol{I} - \boldsymbol{D})^{-1}, \quad k \to \infty, \quad \boldsymbol{D}^k = [0]_{n \times n}$$

$$(D = [d_{ij}]_{n \times n}, \ 0 \le d_{ij} < 1, \ 0 < \textstyle\sum_{j=1}^{n} d_{ij} \le 1, 0 < \sum_{i=1}^{n} d_{ij} \le 1)$$

**Step 4: Analysis**

The sum of the rows is $\sum_{j=1}^{n} t_{ij} = t_i$, while the sum of the columns is $\sum_{i=1}^{n} t_{ij} = t_j$. The vectors are represented by Eqs. (5) and (6). The horizontal axis vector ($r + c$) is accessed ($r = (r_1, \dots r_i, \dots r_n)'$, $c = (c_1, \dots c_i, \dots c_n)'$. It represents the strength of the relationship between the indicators, which is centrality. Similarly, the vertical axis vector ($r - c$) is obtained, which represents the strength of the indicator's influence, which is the degree of cause. In general, when ($r - c$) is positive, the indicator belongs to a cause group, and on the contrary, if *(r - c)* is negative, the indicator belongs to an effect group.

$$\boldsymbol{r} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n \times 1} = [t_{i\cdot}]_{n \times 1} = (r_1, ..., r_i, ..., r_n)' \tag{5}$$

$$\boldsymbol{c} = \left[\sum_{i=1}^{n} t_{ij}\right]'_{1 \times n} = [t_{\cdot j}]_{n \times 1} = (c_1, ..., c_j, ..., c_n)' \tag{6}$$

$$(T = [t_{ij}]_{n \times n},\ i, j = 1,2, \ldots, n)$$

**Step 5: Relationship Map**

When ($r + c$) is on the horizontal axis, and ($r$ - $c$) is on the vertical axis, the criterion coordinates ($r + c$, $r$ - $c$) are marked on the graph. If there is an influence relationship between indicators, the causal relationship diagram can be drawn by linking them with the arrows. The diagram helps decision-makers to construct network relationship diagrams effectively. *(r + c)* presents the degree of centrality or the degree of association, which indicates the degree of influence between the indicators. The degree of centrality presents the strength of the association of the indicator in the group of problems. The larger the value, the higher the relevance of the indicator. ($r$ - $c$) is the degree of cause or the degree of influence, which indicates the degree of difference in the influence between indicators. The value presents the degree of causality of the indicators. When the degree is positive, the indicator has a higher degree of association and is biased toward the cause group, while a negative value indicates that the indicator is biased toward the effect group.

### *2.3. AHP*

ANP is derived from AHP so it is necessary to understand AHP to use ANP appropriately. AHP was proposed by Saaty (1980, 1996) as a decision-making methodology with uncertain and multiple evaluation criteria. In hierarchical analysis, a complex problem is segmented in a structured hierarchical network so that the decision-maker can analyze the problem in a structured way and obtain enough information to choose the most appropriate solution. AHP is used in a three- or four-tier structure to divide the hierarchy into objectives, criteria, sub-criteria, and technical solutions. Comparative calculations are performed to find out how much sub-criteria affect the objectives and select the optimal solution.

### *2.4. ANP*

Problems have dependence or feedback relationships, and as the problem grows complex, the relationship of indicators in the problem becomes more complex. Independence assumptions oversimplify the problem, resulting in biased assessment. To avoid such drawbacks, ANP is used (Saaty, 1980). In ANP, a feedback mechanism is added to the traditional structure of AHP as a network. The development of interdependency between factors is used to find decisions (Saaty, 1996) and identify the organizational structure.

## 3. Research Method

### *3.1.Evaluation criteria*

In DEMATEL, the input values were determined to obtain the impact matrix and evaluate the important market indicators. SPSS was used to calculate evaluation indicators and construct the matrix of ANP(Table 1 Impact matrix). Table 2(Normalized impar matrix.) show mutual influences between six components. Aesthetics showed the highest degree of influence, while delivery had the lowest degree of influence. All components had mutual influence directly or indirectly. Productivity and aesthetics had the highest degree of influence on each other. Productivity and deliverability had the lowest degree of influence on each other(Table 3). Operability, practicality, aesthetics, safety, and functionality were influenced by other criteria belonging to the effect group.

**Table 1.** Impact matrix.

| | Practicality | Delivery | Productivity | Aesthetics | Functionality | Operability | Overall |
|---|---|---|---|---|---|---|---|
| Practicality | 0 | 1.428571 | 1.428571 | 2.285714 | 0.857143 | 1.285714 | 0.571429 |
| Delivery | 1.714286 | 0 | 2.142857 | 1.571429 | 1.142857 | 0.857143 | 0.714286 |
| Productivity | 2.142857 | 2.428571 | 0 | 2.285714 | 1 | 1.571429 | 0.857143 |
| Aesthetics | 2.428571 | 2 | 1.857143 | 0 | 0.857143 | 1.142857 | 0.714286 |
| Functionality | 1.714286 | 1.857143 | 1.285714 | 1.571429 | 0 | 0.714286 | 0.571429 |
| Operability | 1.857143 | 1.428571 | 2.142857 | 2.285714 | 0.857143 | 0 | 1 |
| Overall | 1.285714 | 1.571429 | 1.857143 | 1.571429 | 0.714286 | 1.428571 | 0 |

**Table 2.** Normalized impar matrix.

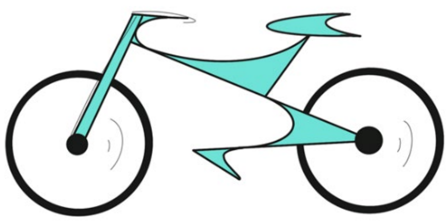
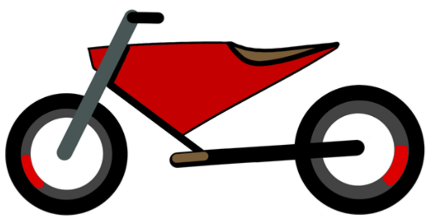
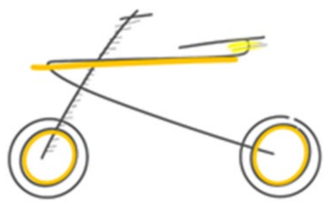
| D=A×S | Practicality | Delivery | Productivity | Aesthetics | Functionality | Operability | Overall |
|---|---|---|---|---|---|---|---|
| Practicality | 0 | 0.138889 | 0.138889 | 0.222222 | 0.083333 | 0.125 | 0.055556 |
| Delivery | 0.166667 | 0 | 0.208333 | 0.152778 | 0.111111 | 0.083333 | 0.069444 |
| Productivity | 0.208333 | 0.236111 | 0 | 0.222222 | 0.097222 | 0.152778 | 0.083333 |
| Aesthetics | 0.236111 | 0.194444 | 0.180556 | 0 | 0.083333 | 0.111111 | 0.069444 |
| Functionality | 0.166667 | 0.180556 | 0.125 | 0.152778 | 0 | 0.069444 | 0.055556 |
| Operability | 0.180556 | 0.138889 | 0.208333 | 0.222222 | 0.083333 | 0 | 0.097222 |
| Overall | 0.125 | 0.152778 | 0.180556 | 0.152778 | 0.069444 | 0.138889 | 0 |

**Table 3** Total impact relationship matrix (T)

| T= | Practicality | Delivery | Productivity | Aesthetics | Functionality | Operability | Overall | | |
|---|---|---|---|---|---|---|---|---|---|
| Practicality | 0.838506 | 0.914685 | 0.90519 | 1.034041 | 0.511356 | 0.650928 | 0.404593 | 5.259299 | 6 |
| Delivery | 1.0043 | 0.818759 | 0.97825 | 1.008421 | 0.547474 | 0.63577 | 0.425873 | 5.418847 | 5 |
| Productivity | 1.222424 | 1.186865 | 0.98372 | 1.249402 | 0.634021 | 0.809339 | 0.516317 | 6.602088 | 1 |
| Aesthetics | 1.126826 | 1.047181 | 1.026235 | 0.950573 | 0.562916 | 0.704062 | 0.456022 | 5.873815 | 3 |
| Functionality | 0.948448 | 0.917815 | 0.864353 | 0.949737 | 0.420081 | 0.585435 | 0.390223 | 5.076092 | 7 |
| Operability | 1.152981 | 1.069367 | 1.10907 | 1.200733 | 0.59535 | 0.64791 | 0.507411 | 6.282824 | 2 |
| Overall | 1.002118 | 0.978743 | 0.991623 | 1.039633 | 0.529343 | 0.701725 | 0.376105 | 5.619289 | 4 |
| | 7.295603 | 6.933414 | 6.858441 | 7.432541 | 3.800542 | 4.73517 | 3.076544 | 0.819026 | |
| | 2 | 3 | 4 | 1 | 6 | 5 | 7 | | |

We explored how to improve the product design of three Balance Bikes (Table 4)to verify the feasibility of DEMATEL. We conducted two questionnaire surveys to determine the causal relationship between the factors that affected the consumers' decision to purchase Balance Bikes. Personal interviews were also conducted to obtain the respondents' views and detailed information. The data of the questionnaire surveys was analyzed using SPSS. The questionnaire was distributed to 25 respondents, 23 of which passed the consistency test, 2 of which were considered invalid. All respondents were university students. First bullet

**Table 4.** Designs of Balance Bikes.

| 1 | 2 | 3 |
|---|---|---|
|  |  |  |
| Simple and versatile design for Balance Bikes | Balance Bike Deflector Design | Simple design for Balance Bikes |

Average values of DEMATEL were calculated (Table 5). Values greater than or equal to the threshold were plotted on a coordinate for comparison (Fig. 1). To show the causal relationship between the criteria clearly, the values larger than the threshold in the impact matrix were retained by using the decision laboratory analysis. From the perspective of criteria, all criteria have mutual influence, either directly or indirectly. Compared to other criteria, aesthetics and delivery showed the highest degree of influence, while practicality and functionality showed the lowest degree of influence. Other indicators were influenced by those criteria.

**Table 5.** Average values of DEMATEL.

| | Practicality | Delivery | Productivity | Aesthetics | Functionality | Operability | Overall |
|---|---|---|---|---|---|---|---|
| Practicality | 0.838506 | 0.914685 | 0.90519 | 1.034041 | 0 | 0 | 0 |
| Delivery | 1.0043 | 0 | 0.97825 | 1.008421 | 0 | 0 | 0 |
| Productivity | 1.222424 | 1.186865 | 0.98372 | 1.249402 | 0 | 0 | 0 |
| Aesthetics | 1.126826 | 1.047181 | 1.026235 | 0.950573 | 0 | 0 | 0 |
| Functionality | 0.948448 | 0.917815 | 0.864353 | 0.949737 | 0 | 0 | 0 |
| Operability | 1.152981 | 1.069367 | 1.10907 | 1.200733 | 0 | 0 | 0 |
| Overall | 1.002118 | 0.978743 | 0.991623 | 1.039633 | 0 | 0 | 0 |
| D+R | 12.5549 | 12.35226 | 13.46053 | 13.30636 | 8.876634 | 11.01799 | 8.695833 |
| D-R | -2.036304 | -1.514567 | -0.256353 | -1.558726 | 1.27555 | 1.547654 | 2.542745 |

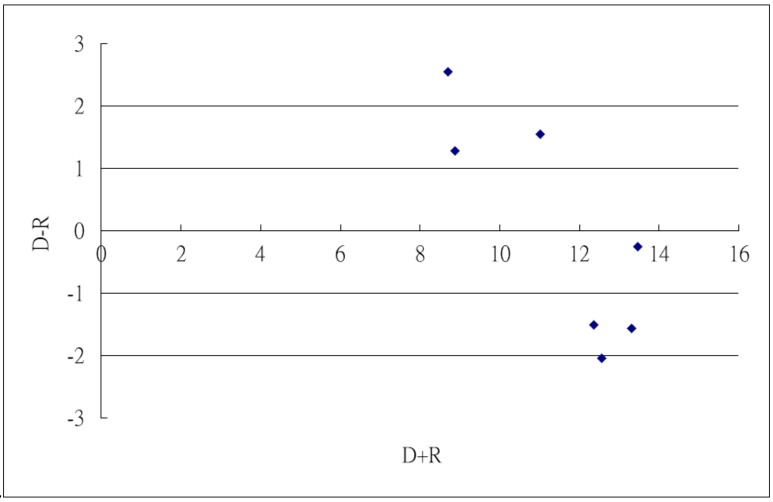
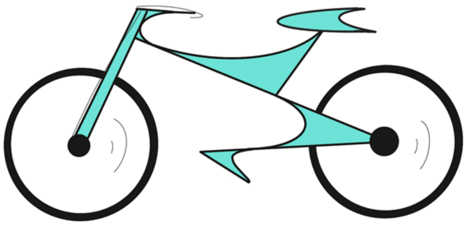
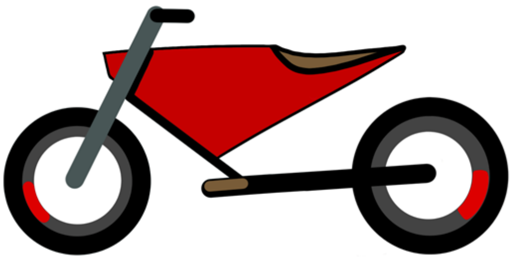
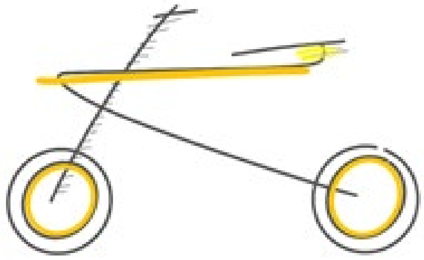



**Fig. 1.** Distribution of D+R and D–R.

For the three Balance Bike designs, the T values were calculated as shown in Table 6. Design 1 showed the highest value of T and Design 3 showed the lowest value. The respondents preferred Design 1 and valued aesthetics and delivery most.

**Table 6.** DEMATEL average(T)

| No. | T | Balance Bike designs |
|---|---|---|
| 1 | **T** = 0.842 |  |
| 2 | **T** = 0.752 |  |

| | | |
|---|---|---|
| 3 | **T** = 0.561 |  |

## 4. Conclusions

Using DEMATEL, the impact matrix and relationship matrix of three Balance Bike designs were obtained to determine important market indicators for product development. DEMATEL results were successfully applied to the case study of Balance Bikes. In addition to the development of partitioning between customers, DEMATEL can used to establish product designs. The design process is not separated from the production development. It is important to understand the relationship between the components in product development, and the result can be used to understand the modularization of products and their manufacture. The results of this study showed that DEMATEL can be applied to various product development processes in which the relationship of components has different degrees of complexity.

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