Tasarım Kuram 2019;15(27):85-99 doi: 10.14744/tasarimkuram.2019.02411

Evaluation of Industrial Designs by Using Analytical Hierarchy Process and Parallel Prototyping

Özkal Özsoy
Mimar Sinan Güzel Sanatlar Üniversitesi, Mimarlık Fakültesi, Endüstri Ürünleri Tasarımı Bölümü

Başvuru tarihi/*Received*: 09.08.2018, Kabul tarihi/*Final Acceptance*: 30.10.2018

Abstract
This article is about the analytic hierarchy process and parallel prototype concepts used in many theoretical and applied fields and their adaptation to the industrial product design process. Firstly the prototype concept is introduced, followed by AHP. The PROMETHEE method, which is included in the study as an additional validation method, is also briefly discussed and then a field study in which product designs are evaluated is presented. Of the various portable lighting product designs previously made, 3 have been selected for use in field study. In order to produce working prototypes of these, designs are modeled on the computer and detailed interior and exterior planning is done in order to be able to produce and use body parts. Body parts are manufactured in 3D printer and electronic circuits designed for them are mounted. The prototypes obtained were evaluated in interviews with 10 designers participating in the study according to the criteria selected and their opinions were saved as research data. This data was then evaluated using the AHP method and re-evaluated by using the PROMETHEE method for verification purposes. As a result of this process, the performances of the designs according to the selected criteria were calculated numerically and the design which will have the highest chance of success in the market was determined. It has been shown that the design evaluations can be made more objective and the accuracy of given decisions can be increased by adapting these tools to decision making and evaluation processes in industrial design. This, in turn, will have a positive impact on overall design quality.

Öz
Bu yazı, teorik ve uygulamalı bir çok alanda kullanılan analitik hiyerarşi süreci ve paralel prototip kavramları ve onların endüstri ürün tasarımı sürecine uyarlanışı üzerinedir. Öncelikle prototip kavramı tanıtılmakta, sonrasında AHP açıklanmaktadır. Doğrulayıcı ek yöntem olarak çalışmada yer alan PROMETHEE yöntemine de kısaca değinildikten sonra içinde ürün tasarımlarının değerlendirildiği bir alan çalışması sunulmaktadır. Alan çalışmasında kullanılmak üzere, daha önceden yapılmış çeşitli taşınabilir aydınlatma ürünü tasarımları arasından 3 tanesi seçilmiştir. Bunların çalışan prototiplerinin üretilebilmesi için tasarımlar bilgisayarda modellenmiş, gövde parçalarının üretilebilir ve kullanılabilir olabilmesi için detaylı iç ve dış planlama yapılmıştır. Gövde parçaları 3B yazıcıda üretilmiş ve içlerine tasarlanan elektronik devreler monte edilmiştir. Elde edilen prototipler, çalışmaya katılan 10 tasarımcıyla yapılan görüşmelerde seçilen kriterlere göre değerlendirilmiş, alınan görüşler araştırma verisi olarak kaydedilmiştir. Sonrasında bu veri AHP yöntemi ve doğrulama amacıyla da PROMETHEE yöntemiyle değerlendirilmiştir. Eldeki tasarımların, seçilen kriterlere göre performanslarının sayısal olarak ortaya çıktığı bu değerlendirme sonucunda piyasadaki başarı şansı en yüksek olan tasarım belirlenmiştir. Bu araçların endüstri tasarımındaki karar verme ve değerlendirme süreçlerine uyarlanmasıyla tasarım değerlendirmelerinin daha objektifleştirilebileceği, verilen kararların doğruluğunun arttırılabileceği gösterilmiştir. Bu da sonuç olarak genel tasarım kalitesine olumlu etki yapacaktır.

Keywords: Analytical hierarchy process, parallel prototyping, industrial design, promethee, design evaluation

Anahtar Kelimeler: *Analitik hiyerarşi süreci, paralel prototipleme, endüstriyel tasarım, promethee, tasarım değerlendirilmesi*

Introduction

In today's rapidly growing global market, good designs, short product development time and low cost define the competitiveness of new products *(Zhai, Khoo, and Zhong 2009, 7072-9)*. While the competition, constraints imposed by the governments and the investment requirements continuously rise, the time available for new product development and their life-cycles continuously decrease, making the development of a successful new product ever more difficult every year *(Keeney and Lilien 1987, 185-98)*.

For the success of a new design, giving right design decisions, identifying design problems correctly and solving them efficiently are vital *(Ayag 2010, 731-56)*. Methodic design evaluation enables the identification of design problems, simplifies decision making the execution other tasks in the process and leads to cost-time reduction. It enables designers to foresee the performance of their creations before market release. It is seen that up to 70% of the development cost for a product belongs to the early phases of its design. Early evaluations on design concepts or design details will reduce the costly delays induced from correcting mistakes later. The necessity of doing it right first time due to competition, have led to many tools and techniques to be adapted for helping designers to evaluate conditions and make the right design decisions *(Dahan and Mendelson 2001, 102-16)*. Parallel prototyping and AHP are such research tools.

AHP is a method which has been well proven in many multi criteria decision making applications in different research fields *(Chen, Occena, and Fok 2001, 413-33)*. Similarly, prototyping is a process which integrates design and manufacturing to obtain better solutions *(Beaudouin-lafon, 2003, 1006–1031)*.

Prototyping

Prototyping is a design and engineering process in which abstract designs are converted into tangible objects enabling design teams to use and test their products *(Beaudouin-lafon, 2003:1006–1031)*. Prototypes objects produced from a design which has been completed to a certain detail level and they give the designers information about product's performance and possible problematic details of the design which have been overlooked on paper *(Hartmann, 2009, 194)*.

Prototyping is an iterative process and every prototype provides information about various aspects of the design step in which it is built *(Houde and Hill 1997, 1-16)*. Prototyping applications in interdisciplinary fields like architecture, product design, help designers to create new design options and share them with others, and integrate them in the design after approval *(Dahan and Mendelson 1998, 1-38)*.

Prototyping is usually done 4 different schemes as visualized in Table 1.

- Single: One prototype is manufactured and tested before production.

- Sequential: A process loop containing iterative tests and corrections on one prototype per cycle is repeated until "a good enough design" is obtained.

- Parallel: Multiple prototypes are manufactured from parallel designs, they are comparatively tested and the best one is selected for further development and market release.

- Hybrid: Design improvement, multiple prototype production and evaluation are repeated until "a design good enough" is obtained *(Dahan and Mendelson 1998, 1-38)*.

After the market and technology is investigated, an effective development team usually generates many concepts, of which 5 to 20 is seriously considered in this selection. In sequential prototyping, the prototype produced from a design selected among these multiple product ideas is subjected to tests. If it is not good enough for the market, fix and test process is repeated until the design becomes satisfactory *(Ulrich, 2011)*.

Parallel prototyping *(Figure 1)* is more suitable for a faster development process. As the prototyping mode is parallel, multiple ideas created by the design team can be prototyped and tested at once. The most successful one among these prototypes can be further developed and released to the market, greatly shortening the time required for market release (Dahan and Mendelson 1998, 1-38).

Advancements in rapid prototyping nowadays enabled product developers to easily produce multiple working prototypes by using one or separate designs. After completing computer models for the body parts and the interior electronics, next step is to 3d print parts and install the electronics making the prototypes ready to use for evaluation. Iteratively prototype evaluating cycles provide more information and feedback for designers to improve their designs *(Beaudouin-lafon, 2003, 1006–1031)*. The computer models produced for rapid prototyping can also be used in production as master models, further improving the product development process *(Park, Son, and Lee 2008, 359-75)*.

Table: 1
Prototyping Schemes

		Time-Frame	
		One period	Multi period
Prototypes per period	1	One-Shot	Pure Sequential
	Multiple	Pure Parallel	Hybrid (Parallel and Sequential)

Analytical Hierarchy Process

Evaluations play an important role in the integration of design and manufacturing

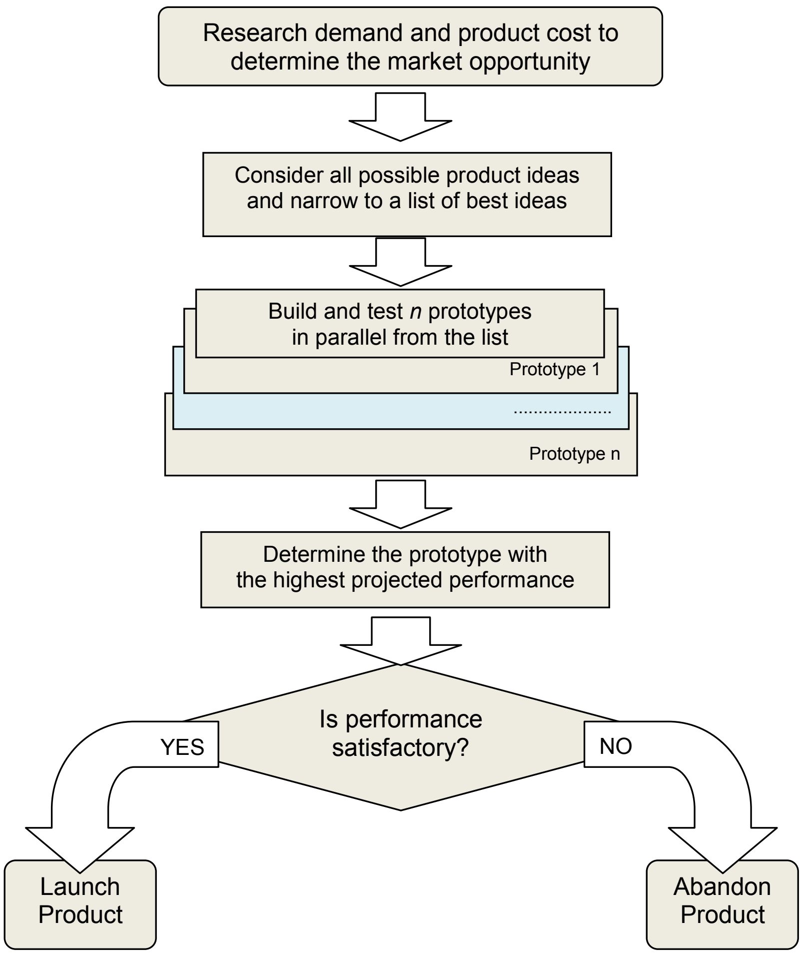


Figure: 1
Parallel prototyping.

(Tomiyama, Umeda, and Yoshikawa 1993, 143-6) and they are important assets to control the design quality. The evaluation process needs to have the necessary means to assess design properties which are hard to measure with usual units.

Many methods proposed for design evaluation seem to lack the flexibility to measure fuzzy design parameters. So evaluation tools which can operate in less known circumstances have been developed or borrowed from other disciplines to help designers' decision making tasks *(Ko 2010, 149-60)*.

AHP is one of these tools and it is first proposed by Myers and Alpert *(Myers and Alpert 1968, 13-20)*, later developed for application in Wharton School of Business *(Saaty, 1980)*. It established a place for itself as a powerful and flexible tool useful for decision making and priority identification applications *(Vaidya & Kumar, 2006:1–29)*. It is a measurement theory based on priority values obtained from pairwise comparisons between criteria and/or alternatives. It is very useful in solving decision making problems belonging to systems that incorporate complex relations with its subsystems and it works by analyzing and modeling these systems heuristically as simplified hierarchical structures and studies them intuitively and logically *(Özden 2008, 300)*. AHP mainly works with weighted scale comparisons which are based on four main axioms *(Saaty, 1986, 841–855)*:

Axiom 1*(Reciprocality)*: If the i^{th} criteria's importance value is x, then the importance value of the j^{th} criteria with respect to the i^{th} criteria shall be $\frac{1}{x}$ (if $a_{ij}=x$ then $a_{ij}=\frac{1}{x}$)

Axiom 2*(Homogeneity)*: Any of the two criteria cannot be infinitely superior to the other.

Axiom 3*(Independency)*: Criteria and alternatives are independent from each other.

Axiom 4*(Hierarchy)*: The human mind can compare things which carry similarities with respect to a common property. If a decision problem or task is divided into sub units and presented within a hierarchical structure similar to the one in Figure 2, every unit at the hierarchy tree has other items next to, above or below to be compared to. So rearranging the units to be compared within a hierarchical order provides extra reference values and simplifies the comparison process.

AHP is realized briefly in three main phases: building a hierarchy diagram, deriving weighted importance and verifying consistencies *(Saaty, 1980)*. The first phase is to convert the decision making problem into a three leveled hierarchy diagram. Then, matrices are prepared for each hierarchy level and they are filled with data obtained from comparisons performed in interviews with participants. Finally, every comparison matrix is solved by using the eigenvector method, which determines the

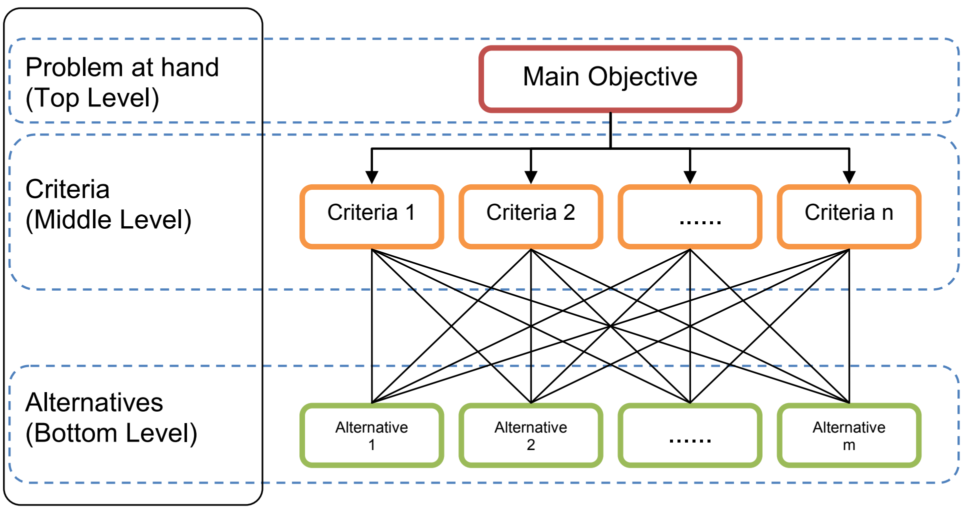


Figure: 2
General Hierarchical Structure of AHP.

relative importance of criteria and performance values of the alternatives.

The AHP application process can be examined in more detail via the flowchart in Figure 3 and the 12 steps in Figure 4.

Promethee Method

PROMETHEE *(The Preference Ranking Organization Method for Enrichment Evaluation)* is one of the multi-criteria decision-making methods developed to select an alternative among many that better suits a specified set of criteria. This method has been developed by Jean-Pierre Brans to provide a simpler alternative to the existing multi criteria decision making methods in the literature due to the difficulties encountered in their application *(Brans 1982, 183-213)*. PROMETHEE is an effective and easy to apply method which is also very suitable to be automated and therefore its use is continuously rising nowadays *(Dağdeviren and Erarslan 2008, 69-75)*. Its users can easily store all the data related to their decision making problem in general purpose spreadsheet software, write formulas into the software at once and have repeating analyzes done by the computer quickly and obtain the results in an easy to understand table form similar to many other methods of multi

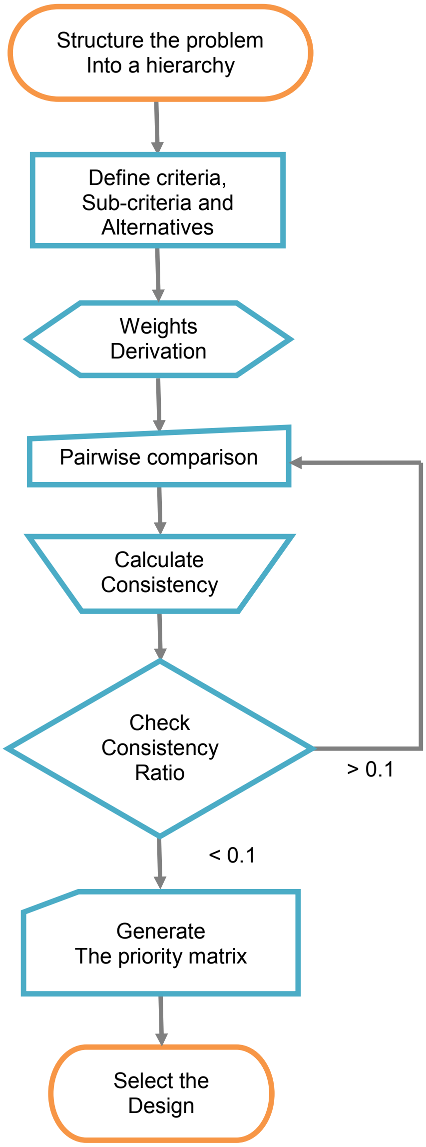


Figure: 3
Flow chart of the Analytical Hierarchy Process.

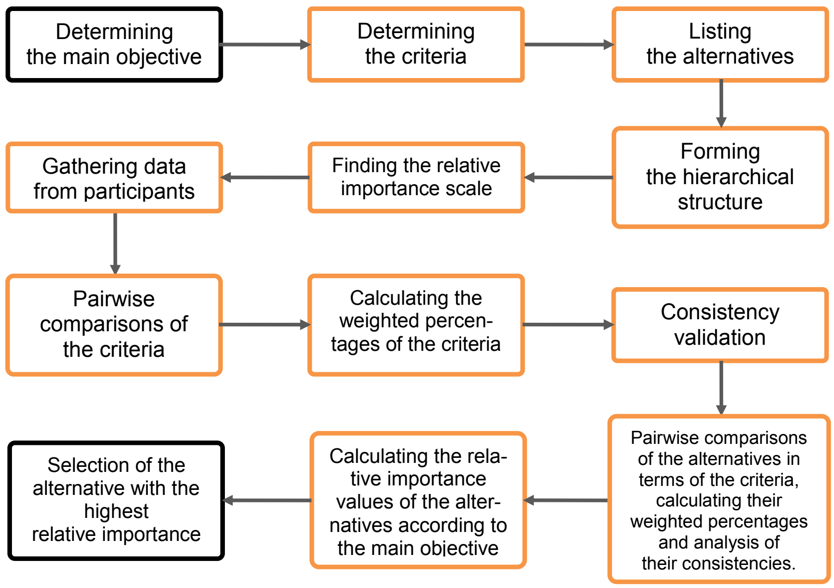


Figure: 4
Analytic Hierarchy Process Steps.

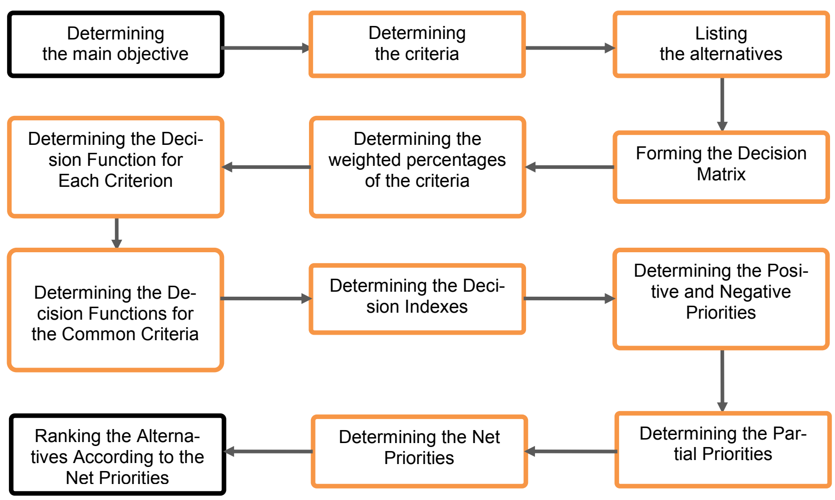


Figure: 5
Implementation Steps of PROMETHEE Method.

criteria decision making. The implementation of the PROMETHEE method is usually carried out in 12 steps, as shown in Figure 5.

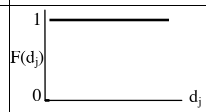
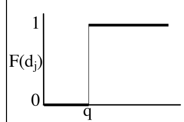
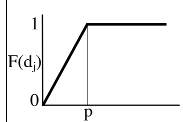
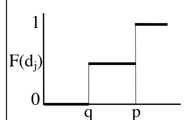
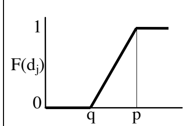
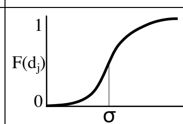
PROMETHEE introduces several types of generalizations for better handling uncertainties, imprecise and/or ill-structured problems *(Ballis, 2007, 213–231)*. It suggests six different general criteria for defining the indifference and preference areas and states. The parameters that specify criteria can be produced by the decision maker according to his/her own considerations.

If N is the alternatives set and M is the criteria set, a preference function is given as the pairwise comparison of the alternatives in each criterion j as:

$P_j(NxN) \rightarrow (O, 1)\ j \in M$ (1)

For the alternatives of a and b:

Table: 2
PROMETHEE parameters and preference functions

Type of Pseudo-criterion	Mathematical Expression	Graphical Form
1. Usual criterion	$f(d_j) = \begin{cases} 1 & d_j > 0 \\ 0 & d_j = 0 \end{cases}$	
2. Quasi-criterion	$f(d_j) = \begin{cases} 1 & d_j > q \\ 0 & d_j \leq q \end{cases}$	
3.Criterion with linear preference	$f(d_j) = \begin{cases} 1 & d_j > p \\ \frac{d_j}{p} & d_j \leq p \end{cases}$	
4. Level criterion	$f(d_j) = \begin{cases} 1 & d_j > p \\ 0.5 & p \geq d_j > q \\ 0 & q \geq d_j \end{cases}$	
5. Criterion with indifference and linear preference	$f(d_j) = \begin{cases} 1 & d_j > p \\ \frac{d_j - q}{p - q} & p \geq d_j > q \\ 0 & q \geq d_j \end{cases}$	
6. Gaussian criterion	$f(d_j) = 1 - e^{-d_j^2/2\sigma^2}$	

$P_j(a,b)=0 \rightarrow$ Indifference between a and b

$P_j(a,b)\sim 0 \rightarrow$ Weak preference of a over b in the j[th] criterion

$Pj(a,b)\sim 1 \rightarrow$ Strong preference of a over b in the j[th] criterion

$Pj(a,b)=1 \rightarrow$ Strict preference of a over b in the j[th] criterion

The preference is a non-decreasing function of the difference d_j between the performances of two alternatives in the j[th] criterion. It is defined as:

$$dj = \begin{cases} P_{aj} - P_{bj} & if\ P_{aj} \geq P_{bj} \\ 0 & Otherwise \end{cases} \quad (2)$$

P_{aj} and P_{bj} are the performances of alternatives a and b in the j[th] criterion and the relation above is valid if j is a maximization criterion; if it is a minimization criterion we must reverse P_{aj} and P_{bj}'s signs and apply Equation *(2)*. Consequently the preference function is defined as:

$P_j(a,b) = f(d_j)$ (3)

The function of f is determined by the decision maker. Six different types of criteria or pseudo-criteria functional forms are generally used as shown in Table 2. Also, three parameter types are defined: The indifference parameter (q), the strict preference parameter (p) and the Gaussian parameter (σ). The type of each criterion, as well as the values of the parameters (q, p and (σ) are decided by the decision maker.

The multi criteria alternative preference index of a over the index of b is defined by weighting the calculated preference functions $P_j(a,b)$ with the weights of importance w_j. The multi criteria preference index π(a,b) represents the intensity of decision maker's preference of alternative a over alternative b. By applying this procedure for alternative pairs, an nxn matrix of alternatives is obtained. The row sum of this matrix determines the outranking character of the corresponding alterative while the column sum represents the outranked character of the corresponding alternative. The greater the row sum of one alternative, the better it is compared to the others. And the greater the column sum of one alternative, the worse it is in comparison with the others. Then the rankings produced by considering the entering and leaving flows are combined to obtain the alternatives' preorder. According to this, the a alternative outperforms b alternative when $\phi^{+}(a) \geq \phi^{+}(b)$ and $\phi^{-}(a) \leq \phi^{-}(b)$ with minimum one absolute inequality. When $\phi^{+}(a) = \phi^{+}(b)$ and $\phi^{-}(a) = \phi^{-}(b)$, a and b are indifferent and incomparable to each other *(Ballis, 2007, 213–231)*.

Incomparability usually arises when one alterative is good according to a criteria group on which the other alternative is weak and vice versa. It can be said that similar situations are frequently happen in real world decision problems *(Brans and Marescal 1990, 217-52)*.

Literature Review

Some studies selected from the relevant literature about prototyping, AHP and PROMETHEE methods are as follows.

Dahan shown that prototypes can be tested realistically by using various methods providing development teams the chance to understand how their products will perform in the hands of the users without investing for mass production *(Dahan and Mendelson 2001, 102–16)*.

Srinivasan, Lovejoy and Beach have worked on parallel prototyping and product design demonstrating that parallel prototyping can reduce the amount of ambiguities of product design conceptualization which are difficult to resolve and stated that parallel approach is more profitable and risk-free than the single step approach *(Srinivasan, Lovejoy and Beach 1997, 154-63)*.

Smith and Reinertson have worked on parallel prototyping in product development and emphasized that design should be fast enough to match the rapidly changing markets of today and parallel prototyping could be helpful for maintaining the pace *(Smith and Reinertsen, 1991)*.

Wheelwright and Clark have worked to evaluate the effects of parallel teams in a design firm to work simultaneously on developing concepts for the same product *(Wheelwright and Clark, 1992)*.

Hauser and Zettelmeyer have produced optimal guidelines for managing research and development portfolios, shown the value of having multiple solution alternatives for a given problem, claiming that it is natural to view multiple parallel prototypes as actual products *(Hauser and Zettelmeyer 1997, 32-8)*.

Liu et al. identified the pros and cons of physical - virtual prototyping and proposed an approach utilizing the integration of both methods for use in evaluation processes *(Liu, Campbell and Pei 2013, 22-8)*.

Borsci et al. considered the users' preferences for six virtual smart phones to define the specifications of a prototype design matching the expectations of users *(Borsci et al. 2014, 1-24)*.

Camburn et al. reviewed six techniques for strategic prototyping to improve prototype performance and reduce cost *(Camburn 2015, 1-10)*.

Muita et al. investigated the ways novel rapid production technology offers competitive advantage to companies, and they concluded that design and manufacture firms should take advantage of this technology to be able to stay in competition *(Muita, Westerlund, and Rajala 2015, 32-7)*.

Camburn and Wood investigated do it yourself manufacturing and reviewed how this approach might be used to convert simple design prototypes to useful products with limited resources *(Camburn and Wood 2018, 1-26)*.

Lanzotti et al. investigated an approach for concept selection by using virtual or 3d printed physical prototypes. They performed a case study in which they designed and produced a number of kitchen mugs and then had some expert participators to evaluate them *(Lanzotti et al. 2018, 1-11)*.

Bao et al. researched the design of simple mechanisms in terms of the interchangeability of sketching and prototyping in the design process. They checked the consumer product design activity for a similar interchangeability *(Bao, Faas, and Yang 2018, 1-23)*.

Day and Riley investigated three-dimensional printing techniques for the design of unique assistive devices. They also did a field study by using several forms they developed and presented a case report *(Day and Riley 2018, 1-5)*.

Panda et al. used AHP and fuzzy TOPSIS approaches for Rapid Prototyping Process selection. They proposed a method to enable decision makers to understand the evaluation process and produce more accurate decisions *(Panda, Biswal, & Deepak, 2014, 1–6)*.

Vaidya and Kumar investigated AHP and shown that it had been used extensively in fields that mostly deal complex decision making and evaluation problems by using qualitative data *(Vaidya & Kumar, 2006, 1–29)*.

Zahedi has shown that the tool's usage is in continuous rise today as it helps the analysis and solution of complex, multi criteria problems with its ease of use and flexibility. He listed the fields of study in which AHP had been preferred as econometrics, statistics, planning, energy management, resource allocation, health, dispute resolution, project selection, marketing, computing technologies, budget allocation, finance, education, sociology, architecture, and many other fields *(Zahedi 1986, 96-108)*.

Ariff et al. used AHP for selecting the best design concept for a automotive front and rear bumpers *(Ariff et al. 2008, 1-18)*.

Hsiao used AHP for planning a concurrent industrial product design process for a musical toy *(Hsiao 2002, 41-55)*.

Henderson and Dutta used AHP to evaluate product design alternatives *(Henderson and Dutta 1992, 275-282)*,

Tam and Tummala used AHP for supplier firms selection during the design-development phase of a communications product *(Tam and Tummala 2001, 171-82)*.

Ayag used AHP methodology to evaluate CAD systems for suitability to product design in terms of abilities of data exchange in supply chain networks *(Ayag, 2015:30–38) (Ayag, 2015:30–38; Dönmez, 2013, 682–689)*

Ayag used AHP for simulating the development of CAD systems *(Ayag, 2002, 3053–3073)*

Dönmez used AHP methodology to investigate CAD software used in industrial design education in Turkey *(Dönmez, 2013, 682–689)*.

Vinodh et al. proposed a model that integrates analytical hierarchy process *(AHP)* with other methods for innovative and sustainable automotive product design *(Vinodh, Kamala, and Jayakrishna 2014, 2758-70)*.

Ahmad et al. researched the conceptual design selection process for a manual wheelchair for elderly by using Analytical Hierarchy Process *(AHP)* and performed a case study to evaluate several sample designs *(Ahmad et al. 2017, 6710-9)*.

Moretti et al. performed a study on using the AHP to develop a tool for prototype evaluation in fashion garment design and industry. *(Moretti, Braghini Junior, and Colmenero 2017, 367-74)*.

Behzadian et al. reviewed the literature on methodologies and applications of PROMETHEE *(Behzadian et al. 2010, 198-215)*.

Prabhu et al. used Fuzzy AHP technique together with PROMETHEE for evaluation and selection of new product ideas for farmers. They tested their proposed model for evaluating single wheeled push cart designs *(Prabhu et al. 2018, 16-22)*.

Wang et al. made a case study in which they evaluated women's shoe designs by using criteria derived from adjectives taken from consumers' daily lives *(Wang et al. 2017, 4900-12)*.

Peko et al. investigated rapid prototyping methods and evaluated them according to several selected criteria by using AHP, PROMETHEE *(Peko, Gjeldum, and Biliă 2018, 453-61)*.

Renzi et al. reviewed decision making processes that can be used in the automotive industry. They classified the decision-making methods according to their use *(Renzi et al. 2017, 1-26)*.

Using AHP for Evaluation of Industrial Design Product Prototypes

After investigating the utilization of the mentioned tools in the literature, it is seen that the AHP method is known to work with both objective as well as subjective input data *(Kuruüzüm and Atsan 2001, 83-105)* and according to the literature, there is no strict number for the amount of samples required. Therefore 10 industrial design students from our university were randomly selected to take part in the study as participants. One on one interviews were conducted with the participants to make the necessary comparisons between the criteria and the design prototypes. To create a common decision for the whole sample group, the geometric mean of the input data was calculated *(Saaty, 2008:83)*. Storage and processing of the data gathered from the interviews were done on EXPERT CHOICE 11 PC software dedicated to AHP and SANNA software for PROMETHEE.

In the process, three design prototypes *(DP)* shown in Figure 5-6-7 were accepted as the input and used in the evaluation.

Figure: 6
3D computer models for the design prototypes (DP) prepared in Solidworks.

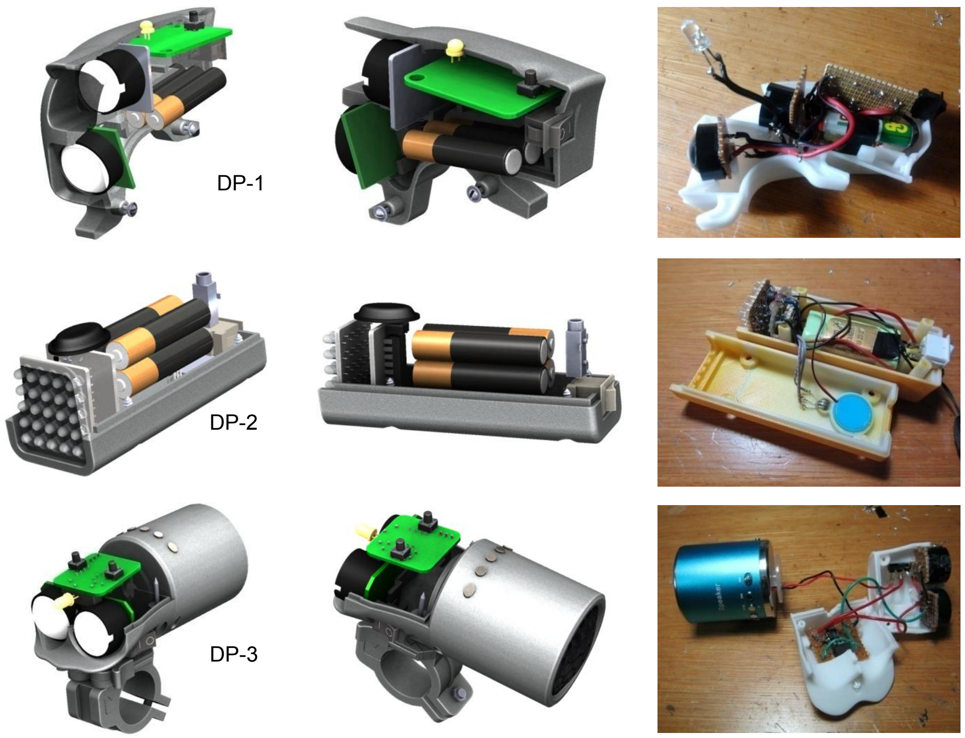


Figure: 7
Manufacturing the design prototypes (DP).

Figure: 8
Photographs of the working design prototypes (DP).

DP-1: Is a powerful lighting product with 1watt LEDs each for high-low beam, and two 5mm daylight running LEDs, has 3 Ni-Mh rechargeable batteries inside and an on off switch at the back. The product has also an emergency mode in which SOS signal is produced by flashing LEDs. The product can be used manually or by attaching to a bicycle handlebar with its secure attachment point and can be charged through a socket on it.

DP-2: Is a lighting product with 5mm LEDs arranged into a 5x5 matrix to obtain better lighting. These 25 LEDs also function as a flat panel dot matrix screen. The product has got intelligent modes of running, in which graphics, animations and information like temperature, time or environment noise level are shown on this dot matrix LED screen. The product has an on off switch at the back and an additional button at the top for adjusting the running modes. The product can be used manually, hanged to a high point from its strap or by attaching to a bicycle handlebar by means of a rubber ring. It has 4 Ni-Mh rechargeable batteries and can be charged through a socket on the top.

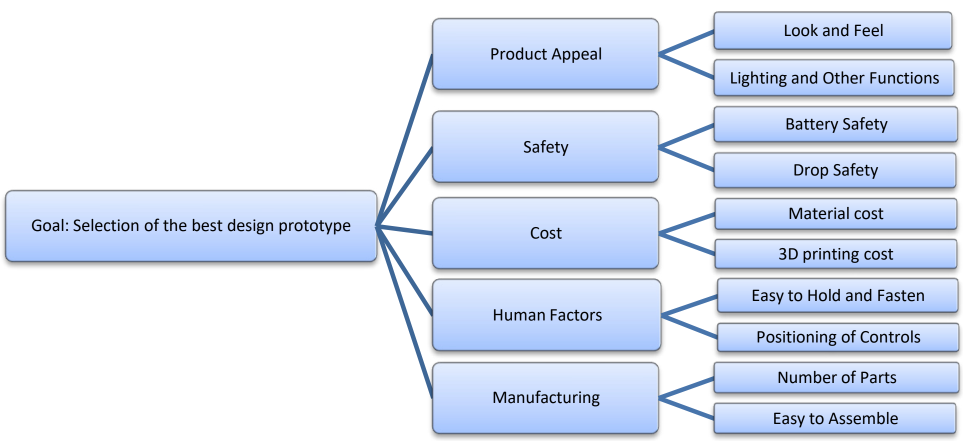
DP-3: Is a powerful lighting product with 1watt LEDs each for high-low beam, and one 5mm daylight running LED, has a single Li-ion rechargeable battery and an on off switch at the side. The product has an emergency flashing mode in which SOS signal is produced by flashing all LEDs. The product has also an mp3 player attached to it and can play music and do lighting separately or simultaneously. Its functions can be adjusted by using the 7 buttons at the top. The product can be used manually or by attaching to a bicycle handlebar with its secure attachment point and can be charged through a socket on the top.

During the evaluation of the design prototypes, the flowchart and the steps of AHP shown in Figure 3-4 are executed. The first step is the definition of the main objective and it is determined as "selection of the best design prototype".

After defining the main objective, the criteria which will be taken into account during selection are defined as: performance, safety, cost, human factors and manufacturing. These main criteria are then divided into 10 sub-criteria as; look and feel, lighting and other functions, battery safety, drop safety, material cost, 3d printing cost, easy to hold and fasten, positioning of controls, number of parts, easy to assemble. After the determination of the criteria and the sub-criteria shown in Figure 8, alternatives DP-1, DP-2, and DP-3 are listed.

At the complete hierarchical structure in Figure 9, the top level shows the main purpose, medium level lists the criteria-sub-criteria and the bottom level lists the alternatives to be evaluated. First the criteria and sub-criteria are used as the input for a PC program specifically designed to be used in the application of AHP. Then empty pairwise comparison matrices generated by the program are filled with data gathered from the participants during the interviews.

Figure: 9
Main goal, criteria and sub-criteria in a hierarchy tree.



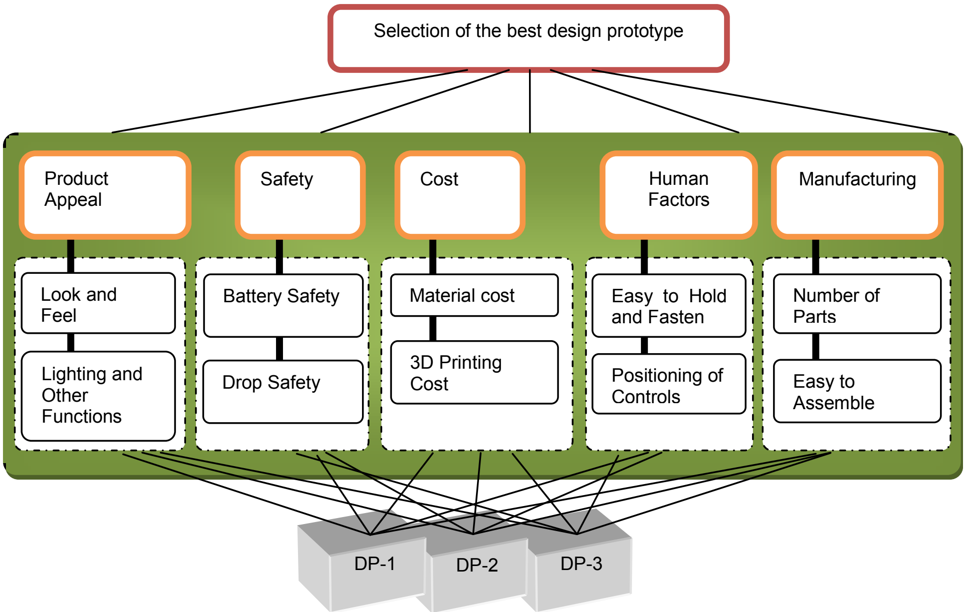


Figure: 10
Complete AHP hierarchical model which will be used in the study.

For the interviews, a private room was prepared with a computer, a table and two seats that the participant and the interviewer used while the participant was asked to do the required comparisons. The interviews usually took between 15 and 20 minutes each. The pictures of the alternatives were shown two by two to the participants on a 23 inch LCD screen for the comparisons. First DP-1 and DP-2 were shown and compared, then DP-1 and DP-3, followed by DP-2 and DP-3. The comparison process always followed this same order for every participant. Each comparison was directed to the participant as an oral question. This oral and visual approach enabled the surveys to be performed easily like an informal conversation. The participants were asked to do the comparative ranking by using Saaty's 1-9 scale *(Table 3)*. Received ranking values were simultaneously entered into the AHP Expert Choice program by the interviewer, saving additional time.

The computer program then executed the sequence of AHP steps shown in Figure 3 which have also been explained in detail in the previous section. With the solution of the model, priorities of the main criteria are ordered from high to low according to weighted importance values, displaying their real world values.

Finally the PROMETHEE method is used for the validation of the results obtained from the AHP method. The same data set and Saaty scale which had been used for

Table: 3
Relative importance scales used in AHP and their definitions

Relative Importance Value	Conceptual Meaning	Explanation
1	Equal value	Two requirements are of equal value
3	Slightly more value	Experience slightly favors one requirement over the other
5	Essential or strong value	Experience strongly favors one requirement over the other
7	Very strong value	A requirement is strongly favored and its dominance is demonstrated in practice
9	Extreme value	The evidence favoring one over the other is on the highest possible order of affirmation
2,4,6,8	Intermediate values	These values should only be used when a compromise is needed.

Table: 4
Results for the pair wise comparisons of the main criteria

Table: 5
General Analysis of the model

- **Goal: Selection of the best design prototype**
  - **Product appeal (L: ,276)**
    - **Look and feel (L: ,257)**
    - **Lighting and other functions (L: ,743)**
  - **Safety (L: ,201)**
    - **Battery safety (L: ,746)**
    - **Drop safety (L: ,254)**
  - **Cost (L: ,159)**
    - **Material cost (L: ,656)**
    - **3D printing cost (L: ,344)**
  - **Human factors (L: ,198)**
    - **Easy to hold and fasten (L: ,746)**
    - **Positioning of controls (L: ,254)**
  - **Manufacturing (L: ,166)**
    - **Number of parts (L: ,284)**
    - **Easy to assemble (L: ,716)**

the AHP are used in the process converting the overall process into an AHP based PROMETHEE sequence. Unlike the process of AHP, 5 types of linear preference functions were determined during the comparison of the main criteria. Then initially pairwise comparisons of the alternatives were done to determine preference indexes. Then positive and negative flow values shown in Table 7 were calculated. The size of the positive flow value gives information about the performances of a particular alternative but as an overall ranking of all alternatives can't be done by using the F^+, PROMETHEE II net flow value *(F)* is calculated.

Findings

According to the findings presented in Table 4, the most important criterion of evaluation is product appeal and it is followed by safety, human factors and manufacturing cost. As the inconsistency ratio is 0.02<0.1, the performed evaluation is successful.

The values for the sub-criteria are also seen in Table 5, together with the values for criteria. When these weighted results are examined, it is seen that "Lighting and other functions" *(74%)* which is a sub-criteria of product appeal, "battery safety"*(74.6%)* which is a sub-criteria of safety, "material cost"*(65.6%)* which is a sub-criteria of cost, "easy to hold and fasten"*(74.6%)* which is a sub-criteria of human factors and "easy to assemble"*(71.6%)* which is a sub-criteria of manufacturing had the highest values and therefore found to be the most important criteria in the evaluation. The consistency ratio is below 0.1, validating these values.

Finally the resulting weighted importance values for the 3 DP alternatives are listed at Table 6 in a decreasing order. Therefore it is seen that DP-2 has the highest weighted importance value *(40.5%)*, followed by DP-3 *(31.4%)* and DP-1 *(28.1%)*. This makes DP-2 as the favored selection by the participants according to the AHP method.

When the results obtained from the PROMETHEE method in Table 7 were checked it is seen that DP-2 receives the highest rank again. As the results from AHP and PROMETHEE match, it is accepted that the AHP results are verified and validated.

According to the overall quantitative findings, DP-2 is the best option among the alternatives in matching the given criteria

Table: 6
Weighted importance values for the 3 DP alternatives

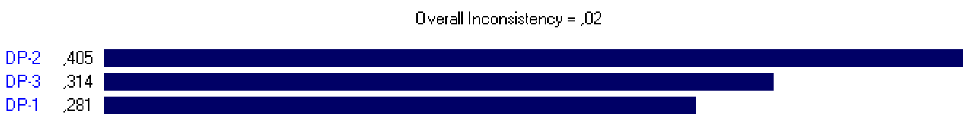


Table: 7
PROMETHEE method results

Ranking	Alternative	F	F+	F-
1	DP-2	0,60000	0,80000	0,20000
2	DP-3	-0,20000	0,40000	0,60000
3	DP-1	-0,40000	0,30000	0,70000

Figure: 11
All three DP prototypes together.

and therefore it is the most suitable design for further development and finally manufacturing.

When a final side by side prototype comparison is done qualitatively by our research team *(Figure 11)*, DP-2 was decided to be visually standing ahead of other DPs with its appealing modern lines that better match to the lines of today's electronic products. As a product it was also found to be a more interesting and fun by our team with its intelligent properties, animated LEDs and informative functions. During our research our team preferred DP-2's feel inside the hand to the feel of the other two due to its simplicity, smaller size and found it safer and easier to use as it lacked sharp corners-edges and controlled by using a single push button. The production cost of DP was also lower than the others as it has only two simple, small body parts and very small printed circuit board that are easily assembled together by means of screws while the others have bigger and more complex body parts. These personal opinions and production facts also confirmed the quantitative results obtained by using the proposed methods.

Conclusion

In this study, the use of AHP and parallel prototyping in industrial design as evaluation and decision making tools is presented. The tools are demonstrated within a field study in which three product prototypes are evaluated according to selected criteria and the most successful one is selected for further design development and manufacture.

The methodology used in the field study is divided into three segments, each consisting of multiple steps. The first segment involves setting up the problem by defining objectives, design attributes, and design concept alternatives. The second segment involves data collection from participators and data entry in to dedicated PC software. And the last segment is the execution of the software to do the necessary calculations for generating the performance scores of the design alternatives. Using computers greatly simplifies the use of the method, ensuring the steps being executed in the right order, preventing mistakes which are likely to happen during manual calculations. It also enables the method to be used for solving more complex problems which would be very hard to implement manually.

The contributions of this article fall into three categories. Firstly, AHP, parallel prototyping and PROMETHEE methods were introduced. Secondly, several ways of visualizing and analyzing these methods and their results were introduced which are useful for clearly understanding and interpreting the findings. Thirdly, the proposed decision making process was demonstrated on an industrial design field study.

We think that this kind of systematic approach, together with working prototypes which have been developed from design sketches, would give design teams a good chance to discover and solve issues which otherwise compromise success. The structure of the used methods, convert a large evaluation process in to a group of smaller decisions which are much easier to make. The use of computer software also speeds up the process, shortening the overall time required.

In closing, it should always be remembered that while the tools used in this study provide advantages that provide a framework for facilitating design decisions under uncertainty, they are only meant to inform and help the industrial designer. The industrial designer is the one who has the ultimate responsibility over the design process and all the decisions in it. We think that this kind of methodic approach can be further researched to be utilized in other tasks of the industrial design process. It is hoped that the ideas and suggestions presented in this study find broader use within industrial design in the future●

Kaynakça

Ahmad, M. N., Maidin, N. A., Rahman, M. H. A., & Osman, M. H. (2017), Conceptual Design Selection of Manual Wheelchair for Elderly by Analytical Hierarchy Process (AHP) Method, *A Case Study*, 12(17), 6710–6719.

Ayag, Z. (2002), An analytic-hierarchy-process based simulation model for implementation and analysis of computer-aided systems, *International Journal of Production Research*, 40(13), 3053–3073. https://doi.org/10.1080/00207540210140059

Ayag, Z. (2010), A combined fuzzy AHP-simulation approach to CAD software selection, *International Journal of General Systems*, 39(7), 731–756. https://doi.org/10.1080/03081079.2010.495190

Ayag, Z. (2015), Cad software evaluation for product design to exchange data in a supply chain network, *International Journal of Supply Chain Management, 4*(1), 30–38. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84949765522&partnerID=tZOtx3y1

Ballis, A., & Mavrotas, G. (2007), Freight village design using the multicriteria method PROMETHEE, *Operational Research*, 7(2), 213–231. https://doi.org/10.1007/BF02942388

Bao, Q., Faas, D., & Yang, M. (2018), Interplay of sketching & prototyping in early stage product design, *International Journal of Design Creativity and Innovation*, 6(3–4), 146–168. https://doi.org/10.1080/21650349.2018.1429318

Beaudouin-lafon, M., & Mackay, W. (2003), Prototyping Tools and Techniques. In L. Eribaum (Ed.), *The Human-Computer Interaction Handbook* (pp. 1006–1031). Hillsdale, NJ: CRC Press. https://doi.org/10.1201/9781410615862

Behzadian, M., Kazemzadeh, R. B., Albadvi, A., & Aghdasi, M. (2010), PROMETHEE: A comprehensive literature review on methodologies and applications, *European Journal of Operational Research*, 200(1), 198–215. https://doi.org/10.1016/j.ejor.2009.01.021

Borsci, S., Kuljis, J., Barnett, J., & Pecchia, L. (2014), Beyond the User Preferences: Aligning the Prototype Design to the Users' Expectations. *Human Factors and Ergonomics in Manufacturing*, 1(24), 8. https://doi.org/10.1002/hfm.20611

Brans, J. P. (1982), No TitleL'Ingenierie de la decision, Elaboration d'instrument d'aide a la decision, Methode PROMETHEE*, Colloque d'Aide a La Decision*, 183–213.

Brans, J. P., & Marescal, B. (1990), The Promethee Methods For Mcdm; The Promcalc, Gaia And Bankadviser Software, In *Readings in Multiple Criteria Decision Aid*. (pp. 217–252). Berlin: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-75935-2

Camburn, B. A., Jensen, D., Crawford, R., Otto, K., & Wood, K. (2015), Evaluation of a Strategic Method to Improve Prototype Performance With Reduced Cost and Fabrication Time, *Proceedings of the 20th International Conference on Engineering Design*, (July), 1–10.

Camburn, B., & Wood, K. (2018), Principles of maker and DIY fabrication: Enabling design prototypes at low cost, *Design Studies*, 1–26. https://doi.org/10.1016/j.destud.2018.04.002

Chen, C. H., Occena, L. G., & Fok, S. C. (2001), CONDENSE: A concurrent design evaluation system for product design, *International Journal of Production Research*, 39(3), 413–433. https://doi.org/10.1080/00207540010002397

Cheng, S. C., Chen, M. Y., Chang, H. Y., & Chou, T. C. (2007), Semantic-based facial expression recognition using analytical hierarchy process, *Expert Systems with Applications*, 33(1), 86–95. https://doi.org/10.1016/j.eswa.2006.04.019

Cheng, S. C., Chou, T. C., Yang, C. L., & Chang, H. Y. (2005), A semantic learning for content-based image retrieval using analytical hierarchy process, *Expert Systems with Applications*, 28(3), 495–505. https://doi.org/10.1016/j.eswa.2004.12.011

Dağdeviren, M., & Erarslan, E. (2008), Promethee SıralamaYöntemi İle Tedarikçi Seçimi, *Gazi Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi*, 23(1), 69–75. Retrieved from http://mmf-dergi.gazi.edu.tr/index.php/MMF/article/view/176

Dahan, E., & Mendelson, H. (1998), *Optimal Parallel and Sequential Prototyping in Product Design,* Stanford University. Retrieved from http://web.mit.edu/edahan/www/ WorkingPaperonNew ProductsandExtremeValueTheorybyDahanand Mendelson.PDF

Dahan, E., & Mendelson, H. (2001), An Extreme-Value Model of Concept Testing, *Management Science*, 47(1), 102–116. https://doi.org/10.1287/mnsc.47.1.102.10666

Day, S. J., & Riley, S. P. (2018), Utilising three-dimensional printing techniques when providing unique assistive devices: A case report, *Prosthetics and Orthotics International*, 42(1), 45–49. https://doi.org/10.1177/0309364617741776

Dönmez, S. (2013), Computer Aided Industrial Design Software Selection in Industrial Product Design Education at Turkey Using Expert Choice Program, *Procedia - Social and Behavioral Sciences*, 106, 682–689. https://doi.org/10.1016/j.sbspro.2013.12.078

Hambali, A., Sapuan, S. M., Napsiah, I., & Nukman, Y. (2008), Use of analytical hierarchy process (AHP) for selecting the best design concept, *Jurnal Teknologi*, 49(A), 1–18. Retrieved from http://www.jurnalteknologi.utm.my/index.php/jurnalteknologi/article/view/188/178

Hartmann, B. (2009). Gaining design insight through interaction prototyping tools, *Design*, (September), 194. Retrieved from http://bjoern.org/dissertation/hartmann-diss.pdf

Hauser, J. R., & Zettelmeyer, F. (1997), Metrics to Evaluate R,D&E. *Research and Technology Management*, (July-August), 1–8. Retrieved from http://web.mit.edu/hauser/www/Hauser Articles 5.3.12/Hauser_Zettelmeyer Metrics for RDE RTM 1997.pdf

Henderson, R. D., & Dutta, S. P. (1992), Use of the analytic hierarchy process in ergonomic analysis, *International Journal of Industrial Ergonomics*, 9(4), 275–282. https://doi.org/10.1016/0169-8141(92)90061-4

Houde, S., & Hill, C. (1997), What do prototypes prototype?, *Handbook of Human Computer Interaction*, 1–16. https://doi.org/10.1016/B978-044481862-1.50082-0

Hsiao, S. (2002), Concurrent design method for developing a new product, *International Journal of Industrial Ergonomics*, 29(1), 41–55. https://doi.org/10.1016/S0169-8141(01)00048-8

Keeney, R. L., & Lilien, G. L. (1987), New Industrial Product Design and Evaluation Multiattribute Value Analysis, *Journal Product Innovation Management*, 185–198.

Ko, Y. (2010), A fuzzy logic-based approach to idea screening for product design, *International Journal of Management Science and Engineering Management*, 5(2), 149–160. https://doi.org/10.1080/17509653.2010.10671103

Kuruüzüm, A., & Atsan, N. (2001), Analitik Hiyerarşi Yönteminin İşletmecilik Alanındaki Uygulamaları, *Akdeniz İ.İ.B.F Dergisi*, (1), 83–105. Retrieved from http://www.acarindex.com/dosyalar/makale/acarindex-1423868948.pdf

Lai, V. S., Trueblood, R. P., & Wong, B. K. (1999), Software selection: A case study of the application of the analytical hierarchical process to the selection of a multimedia authoring system, *Information & Management*, 36(4), 221–232. https://doi.org/10.1016/S0378-7206(99)00021-X

Lanzotti, A., Carbone, F., Grazioso, S., Renno, F., & Staiano, M. (2018), A new interactive design approach for concept selection based on expert opinion, *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 1–11. https://doi.org/10.1007/s12008-018-0482-8

Liu, B., Campbell, R. I., & Pei, E. (2013), Assembly Automation Real-time integration of prototypes in the product development process Real-time integration of prototypes in the product development process, *Assembly Automation Business Process Management Journal Business Process Management Journal*, 33(4), 22–28. Retrieved from https://doi.org/10.1108/01445151311294621

Min, H. (1994), Location analysis of international consolidation terminals using the analytic hierarchy process, *Journal of Business Logistics*, 15(2), 25. Retrieved from http://proquest.umi.com/pqdweb?did=573951&Fmt=7&clientId=20175&RQT=309&VName=PQD

Moretti, I. C., Aldo, B. J., & Colmenero, J. C. (2017), Using the analytic hierarchy process for selecting prototypes in the development process of fashion garment products, *Acta Scientiarum Technology,* 39(3), 367. https://doi.org/10.4025/actascitechnol.v39i3.30053

Muita, K., Westerlund, M., & Rajala, R. (2015), The evolution of rapid production: How to adopt novel manufacturing technology, *IFAC-PapersOnLine*, 28(3), 32–37. https://doi.org/10.1016/j.ifacol.2015.06.054

Myers, J. H., & Alpert, M. I. (1968), Determinant buying attributes: Meaning and Measurement, *Journal of Marketing*, 32, 13–20.

Özden, H. Ü. (2008), Analitik Hiyerarşi Yönetimi İle İlkokul Seçimi, *Marmara Üniversitesi İktisadi ve İdari Bilimler Dergisi*, 24(1), 299–320.

Panda, B. N., Biswal, B. B., & Deepak, B. B. L. V. (2014), Integrated AHP and fuzzy TOPSIS Approach for the Selection of a Rapid Prototyping Process under Multi-Criteria Perspective, *5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014)*, (Aimtdr), 1–6.

Park, H., Son, J.-S., & Lee, K.-H. (2008), Design evaluation of digital consumer products using virtual reality-based functional behaviour simulation, *Journal of Engineering Design*, 19(4), 359–375. https://doi.org/10.1080/09544820701474129

Peko, I., Gjeldum, N., & Bilić, B. (2018), Application of AHP, Fuzzy AHP and PROMETHEE Method in Solving Additive Manufacturing Process Selection Problem, *Tehnicki Vjesnik - Technical Gazette*, 25(2), 453–461. https://doi.org/10.17559/TV-20170124092906

Prabhu, T. P., Chaudhari, H. B., Pathak, A. G., & Rajhans, N. R. (2018), Ideation Selection of a New Product Using Fuzzy Multi Criteria Decision Making and Promethee, *Industrial Engineering Journal*, 10(7). https://doi.org/10.26488/IEJ.10.7.49

Renzi, C., Leali, F., Di Angelo, L., & Angelo, L. Di. (2017), A review on decision-making methods in engineering design for the automotive industry, *Journal of Engineering Design*, 28(2), 118–143. https://doi.org/10.1080/09544828.2016.1274720

Saaty, T. L. (1980), *The Analytic Hierarchy Process*, McGraw-Hill.

Saaty, T. L. (1986), Axiomatic Foundations of the AHP, *Management Science*, 32(7), 841–855. https://doi.org/https://doi.org/10.1287/mnsc.32.7.841

Saaty, T. L. (2008), Decision making with the analytic hierarchy process, *International Journal of Services Sciences*, 1(1), 83. https://doi.org/10.1504/IJSSCI.2008.017590

Smith, P. G., & Reinertsen, D. G. (1991), *Developing products in half the time*, New York: Van Nostrand Reinhold.

Srinivasan, V., Lovejoy, W. S., & Beach, D. (1997), Integrated Product Design for Marketability and Manufacturing, *Journal of Marketing Research*, 34(1), 154-163. https://doi.org/10.2307/3152072

Tam, M. C. Y., & Tummala, V. M. R. (2001), An application of the AHP in vendor selection of a telecommunications system, *The International Journal of Management Science*, 29(2003), 171–182. https://doi.org/10.1109/ICSMC.2004.1399797

Tomiyama, T., Umeda, Y., & Yoshikawa, H. (1993), A CAD for Functional Design, *CIRP Annals - Manufacturing Technology*, 42(1), 143–146. https://doi.org/10.1016/S0007-8506(07)62412-3

Ulrich, & Eppinger. (2011), *Product Design and Development* (4th ed.), McGraw-Hill.

Vaidya, O. S., & Kumar, S. (2006), Analytic hierarchy process: An overview of applications, *European Journal of Operational Research*, 169(1), 1–29. https://doi.org/10.1016/j.ejor.2004.04.028

Vinodh, S., Kamala, V., & Jayakrishna, K. (2014), Integration of ECQFD, TRIZ, and AHP for innovative and sustainable product development, *Applied Mathematical Modelling*, 38(11–12), 2758–2770. https://doi.org/10.1016/j.apm.2013.10.057

Wang, D., Li, Z., Dey, N., Ashour, A. S., Sherratt, R. S., & Shi, F. (2017), Case-Based Reasoning for Product Style Construction and Fuzzy Analytic Hierarchy Process Evaluation Modeling Using Consumers Linguistic Variables, *IEEE Access*, 5, 4900–4912. https://doi.org/10.1109/ACCESS.2017.2677950

Wheelwright, S. C., & Clark, K. (1992), *Revolutionizing Product Development*, New York: The Free Press.

Zahedi, F. (1986), The Analytic Hierarchy Process: A Survey of the Method and Its Applications, *Interfaces*, 16(4), 96–108. https://doi.org/http://dx.doi.org/10.1287/inte.16.4.96

Zhai, L. Y., Khoo, L. P., & Zhong, Z. W. (2009), Design concept evaluation in product development using rough sets and grey relation analysis, *Expert Systems with Applications*, 36(3 PART 2), 7072–7079. https://doi.org/10.1016/j.eswa.2008.08.068