PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

A Pugh Matrix based product development model for increased small design team efficiency

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Abstract: This study proposes a new product development model for small design teams with limited resources, based on the Pugh Matrix. The purpose is to address the various known shortcomings of Pugh Matrix by providing the ability to logically define criteria relationships and weightings and by evaluating new concepts against chosen reference solutions per criterion instead of evaluating against discrete products, thus increasing team effectiveness. The practicality of the proposed model was investigated through a case study, development of a contemporary wall tile based on the traditional Turkish ceramic designs. Findings indicated that a systematic exploratory phase enhanced the understanding of the design problem and its constituents, contributed to the design team’s overall efficacy; the utilization of iterative evaluations revealed the strengths and deficiencies of each design alternative in terms of criteria groups as well as individual criteria; the ability to track criteria relationships revealed the possible impacts of each design decision.

Subjects: Industrial Engineering & Manufacturing; Design; Industrial Design

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PUBLIC INTEREST STATEMENT

The agility of small design teams enables product innovation; however, there is an immediate susceptibility to time frame, budget, and human resource limitations. Considering the issues affecting contemporary product design practices, such as changing market trends, advancements in manufacturing technology, rising significance of management and interpretation of user data, hectic development schedules, ever-transforming psychological factors and social sensibilities, as well as the pressing need for sustainable practices, there is a clear need for a systematic approach to increase small design team effectiveness. This study proposes a new product development model for small design teams with limited resources, based on the Pugh Matrix. The purpose is to address the various known shortcomings of Pugh Matrix by providing the ability to logically define criteria relationships and weightings and by evaluating new concepts against chosen reference solutions per criterion instead of evaluating against discrete products, thus facilitating product innovation in small design team context.
Keywords: design process; product development; Pugh Matrix; Turkish ceramic tile

1. Introduction
Considering the issues affecting contemporary product design practices, such as rapidly changing market trends, staggering advancements in manufacturing technology, rising significance of management and interpretation of massive user data, increasingly hectic development schedules, ever-transforming psychological factors and social sensibilities, as well as the pressing need for comprehensive sustainable practices, it can be argued that the methodological framework outlining the design process gradually became a primary factor for determining the design product's ability to succeed. In the past 70 years many concept development methodologies have been devised such as brainstorming (López-Mesa, 2003; Osborn, 1957), Lateral Thinking (De Bono, 1970), Synectics (Gordon, 1969; Prince, 1970), and Six Thinking Hats (De Bono, 1985) while finding significant audiences among product designers and researchers. Each of these methodologies offers various advantages, however, the correct implementation of any design development methodology demands significant resource commitments regarding time, budget, and staff. The issue of limited resources is further apparent for the more complex product development methodologies employed today, such as Concurrent Engineering (Sohlenius, 1992), Quality-Function-Deployment (Akao, 2004), Design for X (Huang, 1996), and Kansei Engineering (Nagamachi, 1995), all of which aim to increase the efficiency of the design process, raise the quality of the end product, minimize production costs, and shorten the time to market. However, the research highlights several noteworthy disadvantages, in particular, the need for an established infrastructure and expertise, as well as the necessity for extensive time commitments and uncompromised execution (Akao, 1990; Kitsios, 2000; Schütte, 2002). Even though small-scale enterprises found to be more flexible and fit for innovation, these disadvantages are very prevalent in small-scale projects which are more immediately susceptible to time-frame, budget, and human resource limitations (Cash et al., 2012; Modransky et al., 2020). This builds a tendency towards informal approaches and as a consequence, formal methodologies tend to stay under-utilized (Salonen & Perttula, 2005).

In light of these claims, this research proposes a new product development model for small design teams that will guide the development, evaluation, elimination, and improvement of design concepts. The proposed model is grounded on the fundamental principles of the Pugh Matrix (Pugh, 1991; Pugh et al., 1996), which is one among a number of concept evaluation and elimination methods, such as Ulrich and Eppinger’s conceptual evaluation method (Ulrich & Eppinger, 1995), Cross’ Evaluation Method (Cross, 2000), Analytical Hierarchy Process (Marsh et al., 1993), and Adaptable Idea Filter (Toubia & Flores, 2007), and Circle of Innovation (Phillips, 2016). The Pugh Matrix is an evaluation tool for conducting paired comparisons of discrete design concepts.

Figure 1. Steps outlining the process of the proposed development model.
based on previously established criteria (Burge, 2009; Pugh, 1991; Pugh et al., 1996). The paired comparisons are conducted between the design alternatives in development and a relevant reference design. Even though simple to implement, the Pugh Matrix exhibits a number of significant shortcomings (Burge, 2009; Frey et al., 2007; Takai & Ishii, 2004). Due to a singular reference design's inability to satisfy every development criterion in a project, research claims that Pugh matrices, despite being very useful in identifying losing alternatives, are not great for determining a winning design alternative (Roozenburg & Eekels, 1995; Saari & Sieberg, 2004). Another issue is the false identification of promising concepts as undesirable due to the inaccuracy of criteria weight assignments (Mullur et al., 2003). Moreover, Burge (2009) pointed out that the low resolution of the weight scale being used can hinder the robustness of the outcome. Besides, Saari and Sieberg (2004) claimed that a failure to address the link among criteria, therefore the complexity of the design problem, Pugh Matrices fall short as a tool for guiding the design process. The new product development model proposed in this study aims to innovate Pugh Matrix methodology by addressing these particular shortcomings. The new model provides the ability to define criteria relationships and logically assign criteria weights; furthermore, the model attempts to enable effective design development guidance by evaluating against the best reference solutions across the market for each criterion instead of focusing on a singular product. It was hypothesized that the product development model presented in this study would be able to assist small design teams or individual designers to solve the increasingly complex design problems for the contemporary market, and overcome the negative effects of time, budget, and human resource limitations. The practicality of the proposed product development model was investigated through a case study, design development of a contemporary ceramic wall tile based on the traditional Turkish ceramic tile. Details of the case study were provided and further scrutinized to reveal the strengths and weaknesses of the proposed model, as well as observe the influence of the methodology on design process and decision-making.

2. Methodology and process

The proposed product development model in this study is grounded upon is the simplified four-stage design process model defined by Cross (2000). This descriptive model was further elaborated into detailed steps that outline the process of the proposed product development model (Figure 1). The distinct steps of the process are grouped under the following three broad phases: exploration, generation & evaluation, and communication. The progression can be thought as a hybrid approach between prescriptive models with discrete steps (Asimow, 1962; French, 1971, 1985; Pahl & Beitz, 1984) and descriptive models that depict a continuous progression (Gero, 1990; Maher & Poon, 1996; Visser, 1991).

The very first step of the process is establishing a list of design criteria that will ultimately determine the technical and commercial performance of the product as well as its performance in use. The primary purpose at this stage is identifying the variables that will have the greatest potential to influence the design process and the end-product (Grenier, 1990; Simon, 1995). An accurate determination of design criteria necessitates a comprehensive research undertaking, which can include procedures such as surveying literature, databases, reports, statistics, and product specifications or acquiring data via questionnaires, surveys, and focus groups. The research process might further include a holistic evaluation of design decisions, processes, physical and aesthetic properties and positive and negative user comments of similar products currently available in the market. After an initial criteria list is created, it should be further optimized, any overlapping items should be merged, criteria with limited impact should be eliminated. This process also has a secondary function, enabling the design team to familiarize themselves with the criteria and understand their possible impact. Nevertheless, the criteria list in question should not be thought of as a constant list. As the design process progresses and as the command of the design team over the subject matter improves, new criteria can emerge, existing criteria can be modified, or any unhelpful criteria may be eliminated.
The second step is defining the strength and nature of relationships between each criterion pair. A design problem is often made up of a web of interrelated sub-problems that are tackled simultaneously (Buchanan, 1992; Dorst & Cross, 2001). This complex nature of the design problem implies that any design decision made regarding any criterion will impact how well the product will satisfy other criteria. Due to the emergent nature of the design process, the design team will likely lose perspective of the underlying design criteria and instead, focus time and energy on specific aspects of the design problem (Buchanan, 1992; Rittel & Webber, 1973). This underlines the importance of organizing design criteria and interrelationships clearly and legibly, in turn preventing the conceptual disconnect that might occur as the design progresses. As the number of criteria grows, the amount and complexity of criteria relationships to be defined exponentially increase. In this study, a relationship matrix was devised to address the problems mentioned here. This matrix is further planned to act as a visual reference to any designer taking part in the process, as well as the stakeholders involved.

The third step in the development process is determining the weight of each criterion. Criteria weights can be determined by the members of a design team through debates or more technically demanding, resource intensive, and long-term methods, such as Quality-Function-Deployment (QFD) may be employed (Clausing, 1994). User questionnaires or focus group studies may also be utilized for this purpose; however, this might not be optimal for every situation especially when there are time, budget, and human resource considerations, as well as access to required expertise for accurate and consistent application of methodology is limited. In the proposed product development model, which is devised to quickly identify a design pathway and to maintain a unified vision for the product being developed, criteria weights are determined by assessing the total impact of each criterion on the other criteria. The summation of the strength of the previously determined criteria relationships indicate an absolute weight that is later assigned to one of the three relative weight categories: 3) highly essential, 2) essential, and 1) less essential. There are various methods for calculating class intervals in a data group and determining value limits for each class (Gurney, 2018); however, if the data points are limited a more basic approach of arraying values and creating three classes with an

![Figure 2. Design criteria, relationships, and weights.](https://doi.org/10.1080/23311916.2021.1923383)
equal number of members may be employed. It is possible to associate different weight multipliers with weight categories, such as 1, 3, and 9 instead of 1, 2, and 3; if a more pronounced difference is required.

Following the determination of the weight of each design criterion, the fourth step involves compiling products currently available in the market and finding a reference design solution that best meets each criterion. As previously mentioned, it is very rare to have a single reference design satisfy every design criterion of a completely different project. Based on this statement, the product development method proposed in this study relies on finding the best discrete solution in the market for each separate criterion to be used as reference. It is hypothesized that, for each criterion, by focusing on the best solution instead of an average solution, the design quality of the final product will improve. Besides guiding the design process, compiling reference design solutions should also help designers in familiarizing themselves with current market trends and the competition by analyzing a large selection of design solutions within the context of the tasked design problem (Morris, 2009). Since there will be more than one reference solution for each criterion, the most suitable reference from a group of solutions can be determined through discussions among the design team or methods, such as preference rank translation.

As explained during the introduction, the proposed production development method utilizes a modified version of Pugh matrices for the evaluation process. The comparisons in Pugh Matrices are conducted between design alternatives and a reference, which is a discrete product with similar design language to the alternatives in development (Ullman, 2010). The main objective is to identify successful and unsuccessful alternatives by evaluating them against an average design. With this approach, identifying possible points of improvement as well as tracing the detrimental effects of these improvements is not possible, largely limiting the usefulness of the tool. The proposed product development model attempts to address these shortcomings. The fifth step encompasses an iterative development process based on a feedback dynamic incorporated between the generation and evaluation of alternative design concepts (Schön, 1983). A group of initial design alternatives designed by the team based on the foundation established in previous steps will be evaluated against chosen reference alternatives for each separate criterion. The evaluation produces a score for each criterion which is later multiplied by the respective relative weight. Later comparisons can be made based on discrete criteria, criteria group or overall performance. This concept evaluation process will guide the eliminations and improvement of initial design alternatives through several iterations.

The very last step of the proposed development process involves creating prototypes and presentation material for the highest-ranking alternative. The information produced throughout the design process, including research, market analysis and criteria development as well as the evaluation tables spanning numerous iterations and resulting quantitative data are hypothesized to help make a better case to the client and should be included in the final presentation.

3. The case study—exploration phase
In this study, to evaluate the effectivity of the proposed product development model, the design case study focused on the Turkish Traditional Ceramic tile panels. Traditional Turkish ceramic tile was chosen as the subject of the design case due to a rich visual language: a combination of a highly variable three-dimensional form combined with established two-dimensional figure, color, and composition features; a relatively straightforward physical structure and build; and lastly the potential for improvement due to a strict adherence to traditional ways of thinking and doing; all of which create a unique opportunity for comparison. Traditional Turkish ceramic tile has a long history of development and refinement but failed to take advantage of the evolving design thinking or emerging technologies (Oflaz, 2012; Taşer, 2004). This indicates to a great potential for design innovation; however, there is also the necessity of conserving the idiosyncratic features pertaining to conceptualization, visual language, product semantics, manufacturing techniques, and overall finish. Based on this assumption, the initial conceptual framework was outlined as
follows: “achieving a product that conforms to the progressive visual language of contemporary design, but also preserves traditional values.” In accordance with this foundational conceptual statement, 18 design criteria were developed and organized under the following 5 feature categories: shape/form, pattern/décor, composition, union/combination, application/installation (Figure 2). The criteria developed are a result of an exhaustive literature survey on the traditional Turkish ceramic tile design, encompassing an extensive research of tile designs from books, articles, theses, as well as archives of private libraries and renowned artists; revivalist designs and replicas of current generation of artists; and commercial tile designs from catalogues of prominent manufacturers.

The outstanding intention when determining the criteria pertaining to shape/form was preserving the traditional tile design characteristics while rethinking various design features through a contemporary mindset. Traditionally, Turkish ceramic tile has a widely employed form factor featuring minimal seams or grout lines. Some minor formal deviations exist, such as utilizing hexagons. This is taken as an indicator that any exploration of a new “shape/form” was assumed to generate interest and establish a better visual connection with a surrounding contemporary interior. In order to support the emphasis on shape/form, two criteria were concerted: “geometry of boundaries” and “surface topology.” Another criterion, “surface details and relief effect,” was incorporated to conserve various relief and inlay applications seen in traditional tile designs. Lastly, considering the reflective qualities of traditional glaze applications another criterion was included to address the “interaction with surrounding illumination”.

The second category “pattern/décor” includes criteria related to the conservation and innovation of the most prominent visual feature of traditional Turkish ceramic tile: surface decorations and embellishments. The criterion, “overlap with traditional visual language” was included to enable the retention of the visual language of figures, colors, and compositions established over hundreds of years. On the other hand, the newly created visual language was expected to introduce novelty and change to a certain degree. The criterion, “compatibility with contemporary design language” was added to support this outlook. “Relationship with tile geometry” as a criterion emphasized the importance of regulating the relationship between two- and three-dimensional features. There are examples of glazed brick use in architecture before the Ottoman Empire period; however, this technique got abandoned over time. “Ceramic structure and glaze properties” are defined as a criterion to reveal the potential for visual richness present in both ceramic body and glaze, which has been reduced to a set number of procedures in the past several centuries. One of the most sought after qualities of traditional Turkish ceramic tile and many other traditional crafts is the emphasis on manual craftsmanship, often associated with aesthetic worth. In order to explore ways of retaining craftsmanship quality of the product and in order not to diminish its value, the
criterion “impression of handcrafted quality” was created. Considering the minimalist tendencies in contemporary design, “repetition effect/visual persistency” was included as another criterion to prevent monotonicity at the level of individual tiling unit.

The third category “composition” comprises two criteria focusing on how the visual features of the tile surface will come together. “Solid/void balance” was incorporated to prohibit certain areas of application surface from creating unexpected visual weight and disrupt the overall sense of uniformity due to the lack of negative space balance of newly generated patterns. On the other hand, “visual unity/consistency” was added to prevent visual dissimilitude due to unusual tile geometry and surface topology and to establish continuity between units of a tile composition.

Both criteria included in the fourth category, “joining/combination” focus on alternating tile combinations. “Combination flexibility/variability” was included to improve the product’s ability to adapt to varying contexts, concepts, and tastes; allowing for creative applications extending beyond what was initially envisioned. The intention behind identifying “combination monotonicity” as a criterion was the following assumption: as the tile geometry gets complicated combination flexibility will be affected negatively; therefore, the resulting effect of overall monotonicity should be controlled.

The last criteria category “application/maintenance” comprises four items that focus on improving the practicality of application, simplifying cleaning and maintenance processes, and extending product lifetime. “Application surface properties” was included as a criterion to ensure that long-term adhesion can be achieved especially in outdoor conditions, by focusing on the back-surface details of the tile. The second criterion “joint/seam detail solutions” focuses on protecting application consistency and professional look, which might be directly affected by intermediary details between each tiling unit during tile setting and sealant application, especially when overcomplicated tile geometries were involved. As an extension of this criterion, the “probability of application defects” was added to address the fact that the average installer might have trouble carrying over his/her traditional tile setting experience. Lastly, to address post-application care, the criterion “ease of cleaning and maintenance” was included.

After the design criteria were developed, the next step was to organize a matrix of relationships between each pair of the 18 items and subsequently, determine the relative weightings. The evaluation was conducted by the members of the design team independently, according to a 3-point scale specifying the strength and with a positive or negative value defining the nature of the relation between the criterion pair. The averages of each designer’s evaluation of each pair were separately calculated to determine the finalized relationship values. During the case study, a total of 153 relationships was defined between each criterion pair. Fourteen relationships were defined as strong positive, 24 were positive, 28 were minimal, 15 were negative, and 15 were defined as strong negative. Fifty-seven relationships were left undefined, due to correlations being very weak or nonexistent (Figure 2).

After the completion of the matrix of relationships, the next step was to determine the relative weightings of the design criteria. As previously explained, the relative weighting of each criterion was determined based on the extent of its influence over other criteria. This is calculated by summing all of the positive and negative relationship values a criterion has, resulting in an absolute weight. For this particular study, in order to translate absolute values into relative values cutoff points were determined to ensure that an equal number of criteria would reside in each weighting group. Resulting absolute and relative weightings of each criterion can be seen in Figure 2. It should also be mentioned that one criterion was assigned to the intermediate group instead of the “less essential” group due to a conflicting cutoff point.

In accordance with the initial conceptual framework and the criteria list, reference design solutions were compiled from 162 distinct products available in the market with relevant features...
Table 1. The evaluation output for each development cycle of the case study

| Criteria Categories | Design Criteria | 1st development cycle | 2nd development cycle | 3rd development cycle |
|---------------------|----------------|-----------------------|----------------------|----------------------|
|                     |                | Alt. 1 | Alt. 2 | Alt. 3 | Alt. 1 | Alt. 2 | Alt. 3 | Alt. 1 | Alt. 2 | Alt. 3 |
| Geometry of boundaries | Designer 1 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 |
| Designer 2 | 0/0 | −1/3 | −1/3 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Surface topology | 15/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 |
| Designer 1 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Designer 2 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Interaction with surrounding illumination | 5/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 |
| Designer 1 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Designer 2 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Category adjusted scores total | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 | −2 |
| Pattern décor | Overlap with traditional visual language | 14/3 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Designer 1 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 |
| Designer 2 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Compatibility with cont. design language | 13/2 | −1/2 | 0/0 | −1/2 | −1/2 | 0/0 | 0/0 | 0/0 | 0/0 |
| Designer 1 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Designer 2 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Relationship with tile geometry | 10/2 | −1/2 | −1/2 | −1/2 | −1/2 | −1/2 | −1/2 | −1/2 | −1/2 |
| Designer 1 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Designer 2 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Ceramic structure and glaze properties | 23/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 | −1/3 |
| Designer 1 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Designer 2 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Impression of high-quality durability | 7/6 | −1/4 | 0/0 | −1/4 | −1/4 | −1/4 | −1/4 | −1/4 | −1/4 |
| Designer 1 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Designer 2 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Repetition effect/visual persistency | 13/2 | −1/2 | −1/2 | −1/2 | −1/2 | −1/2 | −1/2 | −1/2 | −1/2 |
| Designer 1 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Designer 2 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 |
| Category adjusted scores total | −3 | −3 | −3 | −3 | −3 | −3 | −3 | −3 | −3 |

(Continued)
### Table 1. (Continued)

| Criteria Categories | Design Criteria | Absolute weight/Relative weight | 1st development cycle | 2nd development cycle | 3rd development cycle |
|---------------------|-----------------|----------------------------------|-----------------------|-----------------------|-----------------------|
|                     | Designer 1      | Designer 2                       | Designer 1            | Designer 2            | Designer 1            |
| Composition         | 6/4             | −1/1                             | −1/1                  | 0/1                   | 0/1                   |
|                     |                |                                  |                       |                       |                       |
| Visual quality       | 14/3            | −1/3                             | −1/3                  | −1/3                  | −1/3                  |
|                     |                |                                  |                       |                       |                       |
| Category adjusted score total | 4                  | 0/1                           | 0/1                   | 0/1                   | 0/1                   |
| Uniform Combination  | 14/3            | −1/3                             | −1/3                  | −1/3                  | −1/3                  |
|                     |                |                                  |                       |                       |                       |
| Category adjusted score total | 9/2              | −1/2                           | −1/2                  | −1/2                  | −1/2                  |
| Application/ Maintenance | 5/1            | −1/1                             | −1/1                  | −1/1                  | −1/1                  |
|                     |                |                                  |                       |                       |                       |
| Category adjusted scores total | 9/2              | −1/2                           | −1/2                  | −1/2                  | −1/2                  |
| Overall averaged score | −22.5          | −17.5                           | −24.5                 | −9                    | −6.5                  |

**Legend:**
- Designer evaluation adjusted weight: Each design is evaluated against a set of predefined criteria, and the weight assigned to each criterion is adjusted for each design.
- Criteria: Consistency, combination variability, monotonicity, ease of cleaning and maintenance, application and maintenance properties, joint/watertight details, probability of application defects, and adjusted scores.
to the design case. This process was carried out by the members of the design team, independently. Consequently, all samples were brought together, and identical solutions were eliminated from the list. The reference visuals were evaluated according to the preferential ranking methodology previously explained and for each criterion, one design solution was opted.

4. The case study—generation & evaluation phase
Following the determination of the reference design solutions, based on the foundation established in the previous steps, three distinct design alternatives were developed (Figure 3). The initial design development was informed by the previously established criteria, criteria relationships, and weightings as well as the reference design solutions. The focus was to develop a novel tile form that could integrate into contemporary environments yet conserve ties with the traditional visual language by referencing the historic pattern/décor characteristics. Accordingly, the emphasis was placed on the shape/form and pattern/décor categories. The other criteria categories, composition, union/combination, and application/maintenance, were considered secondary at this initial stage.

The evaluation of the initial design alternatives was conducted by the two members of the design team independently. Each design alternative was compared with the previously determined reference design solution for each criterion and was given a score based on its relative success (+1), equivalency (0), or failure (−1). The score was later multiplied with the relative weight of the criterion in question. The positive and negative values were compared individually and cumulatively to determine the general success score of each design alternative (Figure 3). For the first
An analysis based on criteria groups reveals that all three alternatives failed to satisfy the highly essential criteria, “surface topology” under the shape/form category. Considering the strong relationship between “surface topology” and “interaction with environmental light” as well as the proportional relationship between “surface details and relief effect,” it was predicted that any positive effect achieved for one criterion should contribute to the improvement of overall design in terms of the other two criteria (Table 1). Therefore, it was deemed important to pay close attention to the three dimensionality of the surface during the next iteration of design development.

Considering the close criteria relationships within the pattern décor category, it was predictable to see that almost every criterion was evaluated poorly. All three concept alternatives failed to satisfy “overlap with traditional visual language,” which was important in terms of criteria weight but there was a conceptual significance as well. It was hypothesized that focusing on this criterion during the next iteration should help achieve significant improvement. For this particular criterion, however, the strong negative relationship with “compatibility with contemporary design language” suggested that any design decision should involve caution. Another criterion requiring careful attention at this point was “ceramic structure and glaze properties,” for which strong negative relationships within composition and union/combination categories signaled possible balancing issues in future iterations.

The evaluation results at this initial stage also indicated that “visual unity/consistency” was also evaluated poorly. Considering this criterion has a close relationship with “overlap with traditional visual language,” it was assumed that emphasizing this criterion would generate significant improvement. Poor evaluation results were also manifested in the union/combination category. This pointed at the necessity of creating further emphasis on both criteria in the next design development cycle as they closely relate to “ceramic structure and glaze properties”—the criterion with the highest absolute weight. The existing negative relationships between “combination monotonicity” suggested a need for careful attention.

When an overall analysis was made, it was seen that all design alternatives produced in the first iteration of design development showed various important deficiencies. In light of the evaluations conducted, “surface topology” and “overlap with traditional visual language” were determined as the primary areas of emphasis for the second design development cycle. Moreover, based on the overall average scores, alternatives 1 and 3 were decided to be given more careful attention.

During the second iteration of the design development cycle, the alternatives were revised, a strong emphasis was placed on the criterion “surface topology”—primarily by interpreting three-
dimensionality of the tile alternatives further. Moreover, since the initial design alternatives failed to satisfy “overlap with traditional visual language,” the graphic patterns were reworked. In this development cycle, the problems emerging under the joining/combination category due to negative correlations were addressed by creating variations for the new patterns. The evaluation results for this iteration indicated that all three revisions were improved. The evaluation scores for the alternatives were +5.0, −0.5, and 0, respectively, suggesting that revised alternatives should perform similar to the reference solutions (Figure 4).

Even though evaluation results suggested a substantial improvement for the shape/form category, it was also seen that there were still features that can benefit from additional improvement (Table 1). For design alternatives 1 and 3, “surface topology” was one such criterion. It was also determined that any plans for improvement in that regard should also consider “interaction with surrounding illumination” due to the strong positive relationship in place. “Surface details and relief effect” appeared to be the weakest feature in this iteration, which was assumed to be further affected by the lack of success in “surface topology” development.

Under the pattern/décor category, it was observed that during the second development cycle, the progress achieved for “overlap with traditional visual language” created a positive side effect for both “relationship with tile geometry” and “impression of handcrafted quality.” On the other hand, “compatibility with contemporary design language” did not show significant deterioration despite expectations based on the strong negative relationship with “overlap with traditional visual language.” This outcome can be attributed to the progression made in terms of “geometry of boundaries.” Despite the limited success, due to the significant criteria weights in the pattern/décor category, it was deemed that the design alternatives created in this iteration required further improvement.

Despite some overall improvement, the evaluation results for the composition category were not satisfactory. It was seen that the improvements achieved in the pattern/décor category were positively influencing the results achieved in this category, however, to a limited extent. This was interpreted as a lack of coordination between pattern/décor and composition features during development. One of the challenges inherent to the product, the negative relationships previously established between various criteria and “visual unity/consistency” seem to be acting as a barrier for successful composition development. It was decided that in the following design development cycle, special care should be given to the dynamic between composition features and décor elements.

Regarding the union/combination category, the reworked design alternatives displayed some improvement. In the next development cycle; however, the complicated negative criteria relationships with the shape/form and the pattern/décor categories point to a need for careful attention as improving one aspect will cause deterioration for another. The progress regarding the application/maintenance category was unsatisfactory. Based on the designers’ evaluation, an optimization of the “application surface properties” was deemed necessary at this stage. Evaluations indicated that the design alternatives were unable to satisfy both the “joint/seam detail solutions” and “probability of application defects” criteria. The strong negative correlation with the “geometry of boundaries” and “surface topology” was interpreted as the primary cause. Consequently, it was assumed that the focus on shape/form presented a significant challenge for the development of application/maintenance features, and it was decided that less effort should be spent on improving the two application/maintenance criteria in question.

In summary, when the overall evaluation scores for the second iteration of the design development cycle indicate that improvements have been achieved for all three design alternatives; however, there was also a clear potential for further improvement. Accordingly, it was determined that there was a need to specifically focus on the following criteria: “surface topology,” “ceramic structure and glaze properties,” “repetition effect/visual persistency,” “solid/void balance,” and
“combination flexibility/variability” with special attention to criteria relationships. The strong positive interrelationships between some of these criteria indicate that any improvements would create a synergistic effect. Based on the negatively correlated relationships between the focused criteria and the criteria residing under the application/maintenance category, it was decided that the efforts in this area should be limited.

In the third iteration of the design development cycle, “surface topology” became more accented, the three-dimensionality of the product became more dynamic with the implementation of curvilinear forms. With regard to “ceramic structure and glaze properties,” a crackle effect on the surface was introduced and visual variability was further improved through the use of additional color-glazed units. Consequently, the alternatives produced during the last iteration performed relatively better in terms of “repetition effect/visual persistency” and “combination flexibility/variability,” probably due to the newly introduced pattern/décor variations (Table 1). Despite the special attention, the “solid/void balance” experienced only slight improvement. The revised design alternatives are shown in Figure 5.

The evaluation results suggest, compared to the previous iterations, the revised design alternatives scored favorably against the reference solutions with regard to shape/form features. In terms of pattern/décor features, the score outcome for “compatibility with contemporary design language” was average. However, this was predicted due to the strong inverse correlation with “overlap with traditional visual language”—this particular criterion was not only conceptually more significant but also carried more criteria weight.

For criteria residing under the application/maintenance category, the evaluation results indicated a performance deterioration compared to the alternatives produced in prior iterations. The increasing complexity of shape/form and pattern/décor features might have created a negative effect on the perception of “joint/seam detail solutions,” “probability of application defects,” and “ease of cleaning and maintenance” criteria. This situation was consistent with the relationships defined between the criteria in question and the results were already expected following the data obtained during the evaluation process of the second iteration.

When evaluations on the level of individual criteria were examined, it was observed that any relationship with “geometry of boundaries” had the most impact on perceived success, pointing to the dominance of the criterion throughout design development. However, this was expected as the conceptual importance and the relative weight of this particular criterion was established from the get-go. Moreover, it is also important to address the relatively low overall performance of the second concept alternative. This outcome can be explained by looking at criteria relationships, as the excessively complicated boundary geometry negatively affected numerous criteria performances. This outcome depicts how criteria relationships are manifesting themselves throughout the design development process. Considering the complex web of interrelationships, it was decided that further effort for improvement might be detrimental to various criteria and ultimately trivialize additional time and energy investment. Accordingly, alternative 1 was deemed the most promising concept at this stage and initial prototypes were prepared as shown in Figure 6.

5. Discussion & limitations
The steps followed during the exploration phase, encompassing the establishment and optimization of the criteria list, determining the nature of criteria relationships, as well as establishing criteria weights, were organized to improve the design team’s awareness of the various aspects of the design problem early on, and enabled the design team to have more control over the design process. It should also be noted that especially for design teams focusing on a specific product type, the knowledge base created during this process can be utilized in future undertakings. The case study illustrates the systematic construction of the foundation for the design process, deepening the understanding of the design problem and its constituents, which provided efficiency in steering product development. The market research conducted for finding reference design
solutions as well as their organization and archival was useful in terms of developing a robust understanding of the newly established criteria within a broader context. The case study involved a number of discussions between team members to find the best possible reference solution regarding each criterion, furthering each member's understanding of the design problem, the criteria involved, and relevant market trends. The preferential rank translation method provided a simple yet democratic mean to determine the final reference design. It is expected that this methodology will mitigate the excessive influence of dominant team member on less experienced ones. The proposed model displays a flexibility of utilizing different decision-making tools as deemed fit.

The evaluation, elimination, and revision cycle is another important aspect of the proposed model. The process focuses not on selecting the best alternative, but an incremental improvement of design alternatives over several development iterations. The case study illustrated that the strengths and deficiencies of each design alternative were clearly revealed in terms of criteria groups and specific criteria. Combined with the ability to see the criteria relationships and the possible impact of each change, a roadmap for further improvement of each alternative could be clearly drawn. During the case study, it was observed that by following relationships between design criteria, the causes for certain negative outcomes were more easily pinpointed and the possible negative effects of the various intended changes were more easily foreseen. Furthermore, at a given revision cycle, the positive properties of alternatives were easily recognized and adapted to the other alternatives in the following revision cycles. Another possible advantage was the way evaluation scores were averaged. For the proposed model, this approach was utilized to ensure that the impact of the lack of experience or knowledge of the members of the design team were absorbed to an extent. Even though not observed during the case study, large fluctuations between evaluation scores or consistently poor consensus might indicate problems regarding the way the criteria list is established. This might be helpful in helping the design team take necessary steps early on. There's also the possibility of further developing the evaluation methodology to consider the designer's experience or status among peers. Another important benefit of an iterative evaluation, elimination, and revision approach was the data documented throughout this process. A timeline was formed with each increment showing a trajectory of development for each alternative, a piece of valuable information for keeping track of the development process as well as a reference for future projects. Moreover, this data can also be utilized as a formidable communication tool for client presentations.

In this study, the design team conducting the case study was limited to two professionals. Even though this approach ensured that complications for this first implementation of the proposed product development model were controlled, leaving diversity of varied backgrounds and experience levels out of the equation, which also meant that the advantages and disadvantages of the proposed model were presented to a limited extent. The second prominent limitation was the case study's focus on traditional Turkish ceramic tile specifically for use in contemporary interiors. This limited the extent of variability and complexity, which was again beneficial for a first implementation. However, it is important that for future research the focus should be more on complex products that involve multiple components.

6. Conclusions
In conclusion, this study proposed a new product development model to regulate design development of products targeted towards the contemporary market, specifically addressing the time, budget, and human resource limitations often encountered by small design teams or individual designers. In terms of academic contributions, the proposed model addressed various shortcomings of Pugh Matrices, by providing the ability to define criteria interrelationships and logically assign weightings. Furthermore, the model attempted to enable effective design development guidance by evaluating against the best reference solution across the market for each criterion instead of focusing on a singular product. The practicality of the proposed model was investigated through a case study, the design of a ceramic wall tile, which revealed various advantages and
disadvantages of the methodology in detail. The resulting prototypes produced through the utilization of this model have won two separate design awards. In terms of practical contributions, as the case study and its award-winning design output illustrate, the product development model proposed in this study presents the potential to enable effective steering of the design process for individual designers and small design teams that contend with prominent budget, time, and human resource limitations.

**Funding**
This work was supported by the Türkiye Bilimsel ve Teknolojik Araştırma Kurumu [216M081], Türkiye Bilimsel ve Teknolojik Araştırma Kurumu [216M081].

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**Citation information**
Cite this article as: A Pugh Matrix based product development model for increased small design team efficiency, Kutay Guler & Denisa Mirela Petrisor, Cogent Engineering (2021), 8: 1923383.

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