Analysis of the Influence of Product Morphology in Innovation Fostering Using Product Phenetics: Dining Chairs as a Case Study

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Abstract.

The achievement of innovation is deemed as essentially beneficial in product design. It helps differentiate products from competitors, increase user satisfaction, and drive market growth. However, knowing the key aspects that make a product be perceived as innovative remains challenging. This study uses the Product Phenetics approach and its Design & Change Space concepts to relate product morphology and innovation. The authors chose fifteen existing dining chairs in the market, gathered their prices, and downloaded 3D files of them from their brands' websites. First, a focus group selected the seven most conventional chairs of the sample. These chairs were aligned with a common reference point and superimposed in a 3D space to obtain the Conventional Design Space (CDS). The remaining chairs, the so-called original ones, were aligned and superimposed one by one on the CDS. The geometry added to the CDS by each of them was identified and the Euclidean distance between each added voxel to the CDS was computed. Considering price as a valid innovation indicator, its value was correlated with each model's cumulative Euclidean distance. The results of the Pearson correlation test between price and distance showed a high and significant correlation ($p<0.01$) between those variables. Although further studies are necessary, it can be concluded that fundamental changes in product morphology can be an innovation driver for product design. At the same time, Product Phenetics can represent a fundamental element for a promising new approach to be used in innovation-oriented conceptual design tasks.

Keywords: Change Space, Conceptual Design, Design Space, Innovation-oriented design, Morphological analysis

1. Introduction

Innovation in product design is a multifaceted concept encompassing various aspects of the product's lifecycle and user interaction (Jain, 2023). Generally, it can be defined as introducing new ideas, functions, and technologies to create new products or improve existing ones. It can also refer to introducing new and creative approaches, algorithms, or tools while designing or manufacturing a product. Its manifestations may include increased utility, enhanced performance, use of new materials, and improved user experience (Panchal et al., 2004). In addition, introducing new product formal attributes to make it look different or more novel is also a way to innovate in product design (Jensen et al., 2023). Unlike early product design, which focused on functionality and performance (Bainbridge, 2004), modern design emphasizes visual appeal and brand identity and strives to establish an emotional connection with users. In this line, most authors argue that the product's formal attributes can be even more relevant than the functional ones to increase product market success (e.g. Liu., 2003; Steele et al., 2008). Thus, users' perceived innovation allows firms to increase the selling price of the product and therefore the final amount of revenues (Roy & Riedel, 1997, Ge & Li, 2024).

Aesthetics, style, and symbolic product attributes are important areas for managing perceived innovation in product development (Castagna et al., 2021; Guo et al., 2014). Designers might develop novel visual styles or forms that attract consumers (e.g., Pandey, 2022, Sinha, 2021), including new colours, materials, shapes, structures, etc. (Rithish, 2022). These condense the designers' innovative wisdom in product morphology, including years of accumulated product development experience, countless genius inspirations, and even luck. In a narrow sense, morphology in product design refers to the study of the form and structure of a product. It includes the local shape of the product, the overall structure, and the relationship between its different parts. Thus, product morphology has richer connotations and is crucial in the user-centered design concept (Chuang et al., 2001; Yang et al., 2023).

Although there are some classic methods to link product formal attributes to users' perception and emotions, such as Kansei Engineering (e.g., Lu et al., 2024; Zhao et al., 2024), Empathic Design (e.g., Ghosh et al., 2017), Conjoint Analysis (e.g. Nag & Goswami, 2023) and Product Semantics Analysis (e.g., Sunstrum et al., 2024), they provide results that are difficult to be generalized because they break down product morphology into a limited set of elements and attributes, discretizing product shapes, and simplifying product's shape representations. However, in line with Gestalt theory, the whole is more than the sum of the parts because people perceive objects holistically (Bloch, 1995; Homburg et al., 2015). Thus, although designers may conceive of products as discrete attributes, they must be aware that users will evaluate them holistically (e.g., Lee & Choo, 2019). A product's holistic impression highly influences consumer responses (e.g., Schreiner et al., 2017) and is affected by processing fluency (e.g., Mas et al., 2020). Fluency occurs when an appropriate combination of design elements leads to effortless, fast, and holistic user perception (Brakus et al., 2014). Fluency increases visual design appeal and consumer pleasure (Mayer & Landwehr, 2018) and positively influences perceived innovativeness (Luchs et al., 2015).

Product Phenetics is a new approach that has recently emerged which allows the user's perception to be related to the whole morphology of products (Artacho et al., 2016, Artacho et al., 2024). It draws inspiration from Phenetics in Biology, which classifies organisms based on overall similarity concerning morphology or other observable traits. In this line, Product Phenetics involves the classification, direct overlay, and comparison of multiple morphologies of products belonging to the same category within a three-dimensional space. Design & Change Space concepts within Product Phenetics enable the visual representation of the initial product solutions. This visualization can foster the designer's creativity for product form and space utilization during the early phases of product development. It strives to serve as a valuable design-assistance tool that establishes morphology as a novel starting point in the design process. To fulfil this objective, a new morphometric analysis software named "ProPheTA" has been explicitly developed (Artacho et al., 2024).

Following the Product Phenetics approach and using the ProPheTA software, the present work analyses the link between the whole morphology of models belonging to a given product category and innovation, as explained in the following sections of the paper.

2. Material and Methods

2.1 Selection of a sample of 15 models belonging to the dining room chairs product family

Some 15 dining chairs were selected, and their market prices were gathered from five high-end brands. All these products were represented in official 3D models that were downloaded from brands' websites. SolidWorks 2021 software was used to convert these downloaded models into STL format and repair them when necessary. The official 3D models have different quality and features. Thus, they were standardized and re-scaled to their real size. The models appeared on multiple retail websites with slightly different prices; therefore, the prices published on the official website were chosen as the reference for this study.

2.2 Classification of chair models by grouping them into Conventional and Original ones.

Five experts, two on furniture design and three on industrial design, classified the dining chairs into conventional and original chairs in a focus group meeting lasting one and a half hours. Experts were called to select the most conventional chairs. First, they worked individually using black-and-white printed photographs of the models. No extra information was given to them, so experts had to choose only considering the morphology of the products. The experts had to look at the chairs' design and classify them as original when showing less common, bolder, and more creative shapes. Another criterion agreed upon was comfort and ergonomics, classifying more ergonomic shapes as more original. Finally, the chairs that were most out of step with the latest trends in furniture design had to be left in the group of conventional chairs.

The experts showed their selection, and the models on which there was consensus were selected and set aside from the sample. The experts then worked in groups with the remaining chairs until a set of seven conventional chairs was defined by consensus, setting the reference group. At the same time, the rest of the chairs were labeled as the original ones, and they served as the research objects in this study.

2.3 Models' alignment criteria selection.

To select the reference point to align the chairs, the product category was assessed from a functional and ergonomic point of view. Dining chairs support human bodies in a sitting posture, so the free seat cushion, the part of the seat that can be used to sit without interfering with the backrest, is the central part that fits the human body to perform its main function. Therefore, all models were aligned to the centre point of the seat cushion. A segment was drawn from the middle point of the cushion's edge to the middle of the junction between cushion and backrest to define the centre point. The geometric centre of the cushion was defined as the centre point of the aforementioned segment, as shown on the left image of Figure 1. The vertical position of the centre point was established to be at half the cushion's height; see the image on the right of Figure 1.

Figure 1. The center of the seat cushion

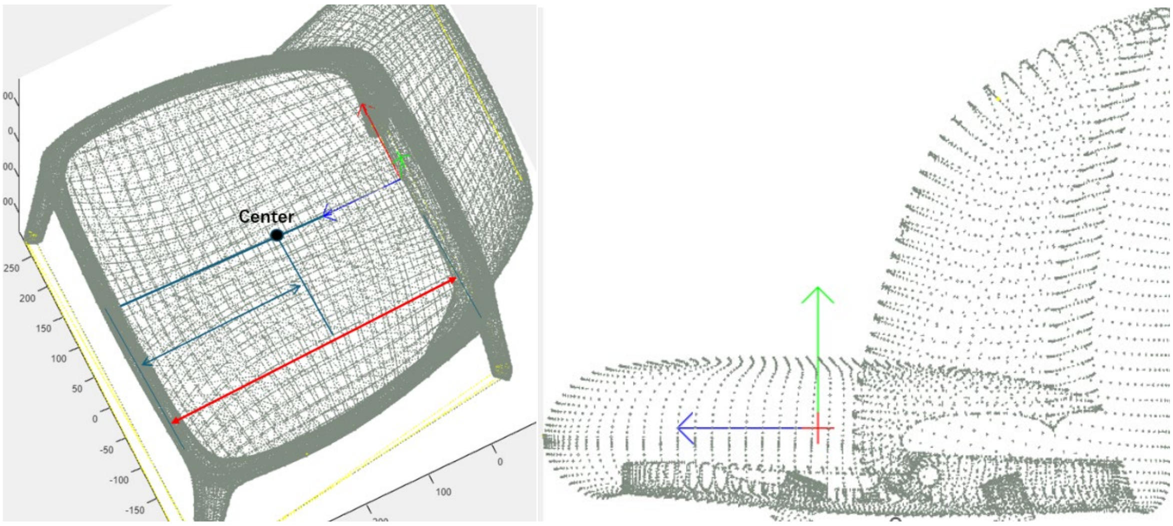


Figure 1. The center of the seat cushion

2.4 Conversion of STL 3D Files to Voxels models

All aligned models, represented in STL files, were converted to a solid spatial representation, facilitating volume comparison. Thus, solid voxels (small cubes) were used, which were closely packed without gaps until the volume inside the STL files was filled. The chosen side length of the voxels was 2.5 mm. The smaller the cube size, the higher the precision; however, more computer resources are required. ProPheTA software was used to complete this task (Artacho et al., 2024), see Figure 2. ProPheTA uses multi-threading technology to harness the full computing power of modern processors to generate these geometric bodies. Consequently, the model conversion time could be reduced to less than one hour. Using a CPU with at least eight physical cores and 32 GB of memory is recommended.

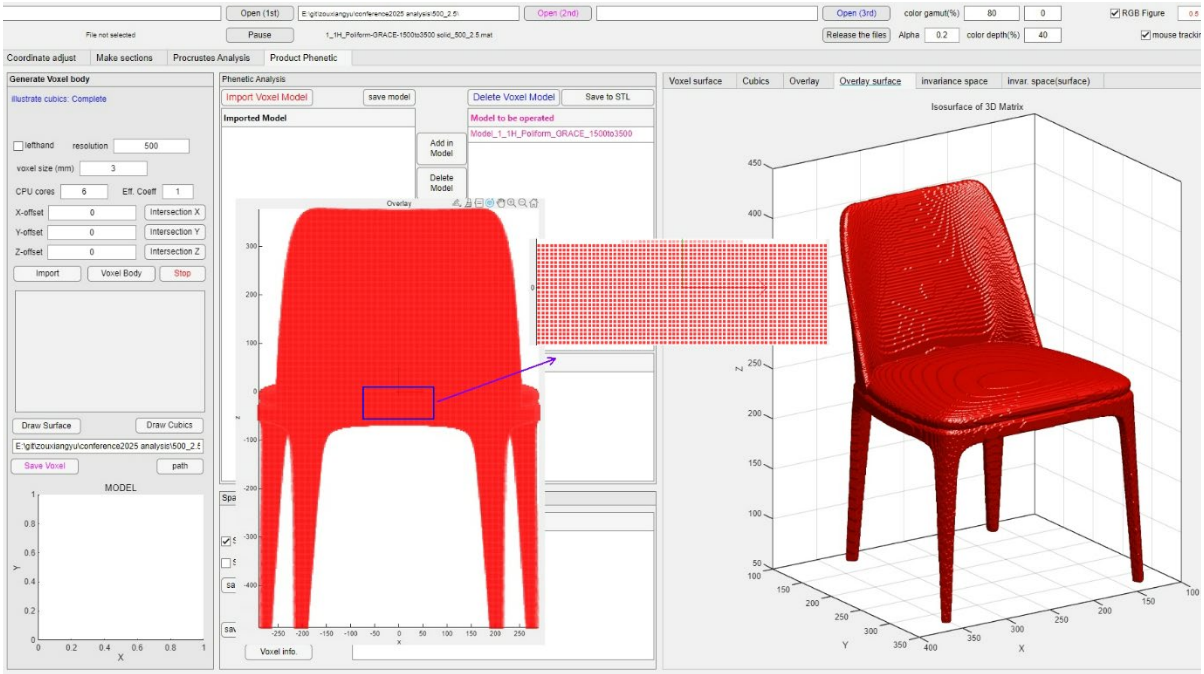


Figure 2. Interface of ProPheTA and its Product Phenetic analysis module.

2.5 Obtaining the Product Design Space and Change Space for the Conventional Group of Chairs

Product Design Space (PDS) is defined by Artacho et al. (2016) as the total volume envelope that covers all the digitized and aligned models belonging to the same product family. Inside the PDS two subspaces can be found: the Functional Invariance Space (FIS) and the Change Space (CS). The FIS is defined by the loci of the points common to all shapes, while the CS is defined as the space where modifications could be made without affecting the product's functional features. Thus, once the chair models were aligned and overlapped, the PDS was determined as the total volume envelope covering all the digitized models belonging to the conventional group of chairs. This PDS is hereinafter referred to as the Conventional Design Space (CDS).

2.6 Computation of the Cumulative Euclidean Distance from the Added Space Generated by Each Original Chair

If a new chair (from the original set) was to be compared with the CDS, the volume of the chair not belonging to the CDS would be considered added space (CS). Figure 3 shows the added space by one novel model. The blue part is the CDS, and the red part is the newly added space for one original model.

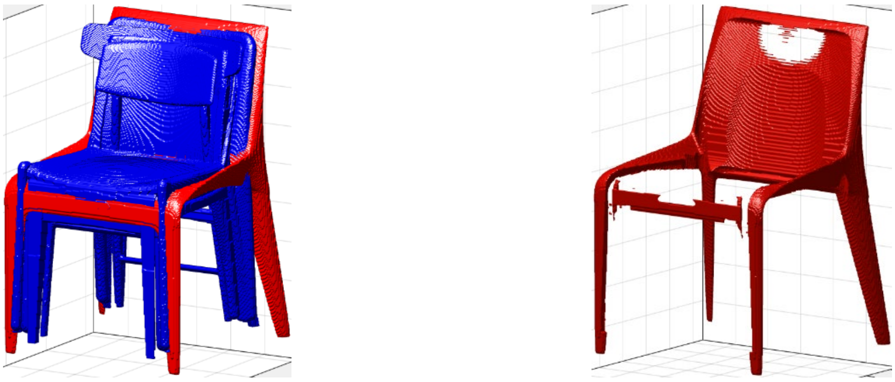


Figure 3. Conventional Design Space (blue) and added space by an original chair(red)

All the voxels contained in the new added space by each original chair were selected and their shortest distance to the CDS was calculated using the Euclidean distance (ED). Thus, the distance between any two voxels in a 3D Euclidean Space is given by the equation 1.

$$ED = \sqrt{(x_{new} - x_{cds})^2 + (y_{new} - y_{cds})^2 + (z_{new} - z_{cds})^2} \quad (1)$$

Where:

$(x_{new}, y_{new}, z_{new})$ are the coordinates in the x, y, and z axes of the new added voxel, and

$(x_{cds}, y_{cds}, z_{cds})$ are the coordinates in the x, y, and z axes of the closest voxel to the new added voxel in CDS.

The sum of all these shortest distances for each original added chair is the cumulative Euclidean distance given by equation 2.

$$Cumulative\ Euclidean\ distance = \sum_i^n ED_i \quad (2)$$

Where:

i is the i-th new added voxel

n is the total amount of new added voxels for each model.

2.7 Analysis of the Correlation Between Price and the Cumulative Euclidean Distance

A Pearson correlation test was performed using SPSS for p<0.01 to test if the cumulative Euclidean distance of each of the new added space obtained by the original chairs was correlated to their price.

3. Results

The following results were obtained after the experimental processes and data analysis explained in section 2 were performed.

Figure 4 shows the chairs experts classified as the most conventional, and Figure 5 shows the original chairs.

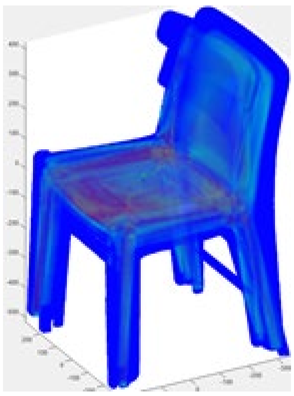
H1 H14 L4 L5 L6 L11 L14

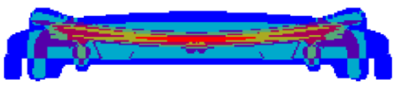
Figure 4. Seven more conventional chairs as the reference group.

L2 L3 L7 L1 H5 H13 H4 H6

Figure 5. Eight novel chairs as the research objects (the original ones)

Figure 6 shows the combined PDS of the seven conventional chairs, which form the CDS (Conventional Design Space). The warmer the colour, the more times shapes overlap at that position.





Cross section of a seat cushion.

Figure 6. CDS overlapped by conventional chairs.

The computation of new added space by the original chairs, not included in the CDS, is shown in Figure 7. The value after the model code is the number of the total amount of new voxels used to represent the new added volume.

Figure 7. Added space of 8 research objects compared to the CDS.

The computation of the cumulative Euclidean distance for each of the original chairs is shown in Table 1. The unit here is the side length of the voxel (2.5 mm). Sorting the original models by price gives Table 2.

Table 1. List of the cumulative Euclidean distance for the original chairs.

Chairs	Cumulative Euclidean distance
L1	705760.22
L2	185775.45
L3	143592.2
L7	3877542.62
H4	10184008.32
H5	2187530.24
H6	8924779.68
H13	7734559.54

Table 2. List of the prices and computed results for the original chairs.

Chairs	Cumulative Euclidean distance	Price (Euro)
L1	705760.22	339
L3	143592.2	489
L2	185775.45	500
L7	3877542.62	589
H5	2187530.24	1800

H13	7734559.54	3211
H4	10184008.32	3500
H6	8924779.68	3500

Pearson correlation test on price and cumulative Euclidean distance shows a strong and significant positive correlation (0.935) for $p < 0.01$.

As can be seen, high-priced chairs such as H4 and H6 are far ahead of low-priced L2 and L3 chairs in the cumulative Euclidean distance index. This example strongly confirms the close positive linkage between the degree of innovation in products' shape and market price.

4. Discussion

This study introduces a quantitative approach based on Product Phenetics to give insights into the relationship between product morphology and innovation. Design Space & Change Space concepts are applied to a set of dining chairs. The results show that differences in morphological space use can be meaningful indicators of product innovation. The strong correlation between the cumulative Euclidean distance of morphological Change Space and market prices validates the proposed approach.

Linking innovation with higher product prices stems from the Price Skimming Strategy used in economics. Price skimming is a strategy in which a product is initially launched at a high price, usually with a higher-than-normal markup, and the price is gradually reduced over time. This approach is commonly used for new and innovative products. As the product becomes less novel and more widely available, its price is steadily lowered (Beltis, 2019). The purpose of this strategy is to accumulate as much profit as possible for the firm during the life cycle of its products. According to the Bass diffusion model in this field (Bass, 2004, Krishnan et al., 1999), people might prefer a product because of two main influences: the innovation effect (p) and the imitation effect (q). Right after a product is launched, early adopters are mainly influenced by the innovation effect (p) since very few people have bought the product yet, thus being willing to pay more for it. The optimal price trend is highly dependent on the repeat purchase rate, which also benefits from product innovation (Lotfi et al., 2024). However, the authors acknowledge that pricing policies may vary among firms and that correlating innovation with higher prices could be difficult to generalize in most cases. Moreover, although using price as a substitute for innovation can be practical, it excludes other factors, such as brand perception and marketing influence, that could affect the results. Thus, future research requires continued efforts to link innovation with morphology more robustly and reliably.

A possible explanation for this correlation between product shape and innovation is the designers' constant search for creative solutions. The main strategies linking design and consumer response are the search for differentiation, diversification, and continuous innovation in markets with a saturated supply of products with the same functionality (Sameti, 2022). Designers have used the product's shape as the leading resource to achieve this differentiation and innovation (Xu, 2020). Searching for new geometries that are creative and attractive to the consumer has been the primary goal of design teams. However, several researchers point out that high levels of novelty can diminish the users' feeling of familiarity (Walter et al., 2020) and involvement with the product (Candi et al., 2017) and can be risky, as it hinders the easy classification and categorization of the product (Wang et al., 2020). The Product Phenetics approach could help mediate between product innovations and product categorization, modulating the meaningfulness of shape-driving creativity. In further works, researchers could set limits within and between products belonging to the same product family using their morphologies, which may help better define differentiation and diversification strategies. Moreover, future studies could draw thresholds for typical/atypical shapes within design spaces to foster innovation without hindering product categorization and fluency.

Despite the explorative nature of the study, the findings could have several practical implications. The Product Phenetics approach and tools such as ProPheTA software could be used to evaluate and refine product morphology during the conceptual design phase. This approach can help designers prioritize creative solutions that align with market expectations and consumer preferences. The study provides a systematic tool for evaluating product morphology, which can improve decision-making processes in product development. Companies can use this approach to differentiate their products in competitive markets by focusing on innovative morphological changes. In addition, Product Phenetics opens up new avenues of research in morphological analysis and its relationship to innovation, user perception, and market performance.

Although the results are promising for this first empirical study, several methodological limitations must also be recognized. The analysis relies on a single product category evaluated with a sample of only fifteen models. Future work must assess a broader range of product categories with larger samples. The perception associated with products is highly dependent on their nature (Wu et al., 2017). Thus, products with different weights between utilitarian and hedonic dimensions should be chosen to see the extent to which the type of product and its context can represent different relationships between innovation and product shape. Moreover, classification between conventional and original models should be based on the user's perception, so that no expert intervention shall be needed in future works.

Notwithstanding these limitations, the study offers a persuasive validation of the Product Phenetics approach and emphasizes its practical usefulness in innovative product development. Considering the whole product morphology, Product Phenetics provides a data-driven and objective framework that could help designers unveil latent information embedded in existing product shapes to be used in innovation-oriented design tasks.

5. Conclusion

This study showed Product Phenetics' potential in exploring the link between product morphology and innovation. Using dining chairs as a case, it quantified added geometric space and its cumulative Euclidean distance to find strong correlations between morphological changes and market price. The findings confirm that product morphology drives innovation, and Product Phenetics can provide designers with a structured way to evaluate and boost creativity in the conceptual design stage.

Furthermore, the development and application of the ProPheTA software have significantly contributed to streamlining the morphological analysis process. It provides an efficient and user-friendly interface to support product design research based on Product Phenetic and shows potential to facilitate informed decision-making and promote innovative outcomes.

Although the results are quite successful and promising, further studies are needed to validate the approach across different product categories and refine the analytical framework. In future research, the application of this methodology is planned to expand across a wider array of product categories. It should include larger and more diverse samples.

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