# Perfumes and Flavors using Scientific Machine Learning

**KEYWORDS:** Perfume engineering, flavor engineering, scientific machine learning, molecule design, product development

**In the period of this report, diverse methodologies in Perfume and Flavor Engineering were applied, spanning from the molecular level to the final formulation. Specifically, within the perfume engineering segment, meta-heuristic techniques and deep learning were employed to discern the optimal formulation for a perfume, achieving the desired fragrance persistently across time and space. Furthermore, transfer learning techniques were skillfully utilized to estimate the odor threshold in perfumes. Turning to the domain of flavor engineering, a triad of distinct machine-learning techniques was independently implemented and synergistically combined. Deep generative models, reinforcement learning, and transfer learning were employed to create diverse natural flavored molecules with a desired flavor for product development.**

## Introduction

Perfume and flavor are essential components in the diverse array of products in modern markets, fostering an ongoing exploration of new scents, tastes, and innovative production techniques. The complexity deepens with the enigma of the human olfactory system, capable of discerning over a trillion distinct smells. Yet, the reasons for its pleasurable responses to specific substances remain elusive. Simultaneously, the challenge intensifies in the field of flavor, defined as the attribute of a substance perceived within the mouth and influenced by the senses of smell, taste, and touch.

This exploration gains particular significance in flavor engineering, especially as the consumption of processed and fast-food products, enriched with various food additives and flavoring agents, continues to rise. Simultaneously, a growing societal awareness of the importance of a healthy lifestyle fuels a demand for foods labeled with natural flavoring agents.

Synthetic molecules, mirroring natural flavor chemicals, play a significant role in designing stable, pure, potent, and cost-effective synthetic flavors. However, this process involves a trial-and-error approach to express the multisensorial complexity inherent in flavors. Stringent legal regulations, especially concerning synthetic chemical processes' environmental impact and potential health risks, underscore the need for meticulous consideration in flavor-based product development.

In perfume engineering within the fragrance industry, two distinct product groups—Fine Fragrances & Cosmetics and Consumer Fragrances — cater to diverse consumer needs. Consumer Fragrances products, such as soaps and toothpaste, leverage pleasant odors to enhance consumer acceptance of functional items, while Fine Fragrances & Cosmetics products, characterized by refined and opulent fragrances, respond to specific customer demands, commanding higher value and budgets for distinctiveness.

An odor, as perceived by a human individual, possesses two crucial properties: intensity (the strength of the smell) and character (what the smell is like). Knowledge of thresholds is paramount for the industry in terms of process functioning (as in the perfume industry) and safety, as many substances can have severe adverse health effects at certain concentrations.

Focusing on perfumes, these liquid fragrance solutions in a suitable solvent represent a convergence of various chemical engineering disciplines. The process of transitioning chemicals from liquid to vapor phase involves well-defined models for vapor–liquid phase equilibrium and gas molecular diffusion. The intricacies of human olfactory detection are scrutinized through psychophysics models, with the integration of Artificial Intelligence (AI) tools shaping the landscape of perfume design.

This increase in interest and exploration transcends fragrance, extending into the broader flavors domain, with research and development (R&D) activities experiencing significant growth. Investments in new flavor-based products reflect an industry poised for expansion. In 2020, the market size for flavors and fragrances in food and beverage products was estimated at EUR 26.53 billion, and projections indicate it will reach EUR 35.52 billion by 2026.

Perfume and flavor engineering, inherently high-cost and time-intensive processes, are now positioned for innovation through the implementation of advanced technologies. Scientific machine learning (SciML) emerges as a promising approach, offering a novel paradigm to streamline processes, reduce costs, and enhance efficiency within the dynamic world of perfumes and flavor engineering.

## Current Development

In the field of perfume engineering, our group introduced an innovative approach, leveraging Deep Learning to assist in simulation-optimization processes. This involved identifying a surrogate model capable of learning the intricate dynamics of perfume release and propagation, correlating it with perception. The model was then applied to optimize the performance of a perfume formulation, consisting of a quaternary mixture. Notably, the developed Deep Neural Network (DNN) models exhibited significantly lower CPU time (0.16 ms) compared to the first-principles model (6 s), enabling efficient prediction of the perfume release's full dynamic behavior, as illustrated in Figure 1.

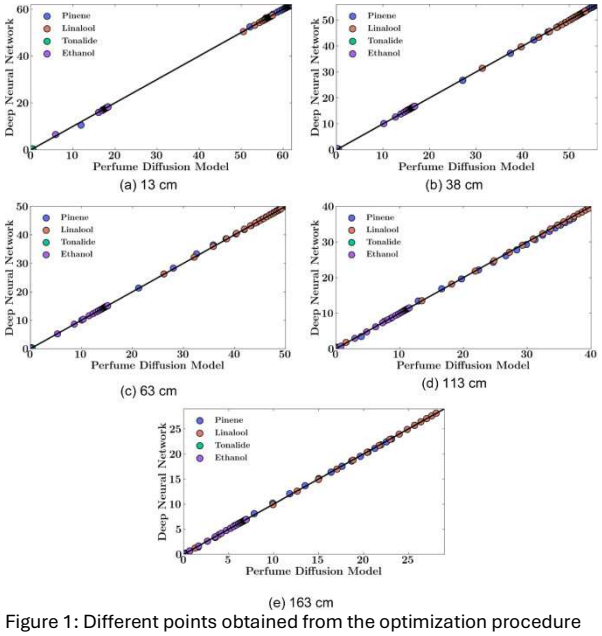


Figure 1: Different points obtained from the optimization procedure tested in the phenomenological model vs their prediction with the DNN model.

Defining, predicting, and designing the performance of fragranced products remains a challenging task. To address this, we presented a systematic methodology for optimal perfume formulation. Utilizing a particle swarm optimization (PSO) method and a single objective function, we sought to determine the ideal perfume composition for achieving a desirable odor spectrum across time and space. Our work proposed the incorporation of a trained recurrent neural network surrogate model, showcasing a substantial reduction in CPU time compared to traditional models.

The study also delved into the creation of a machine learning prediction tool for odor threshold, a crucial parameter in the perfume industry. Employing the concept of transfer learning, we utilized embeddings from a graph convolutional network to predict odor thresholds. Our results indicated that this approach outperformed benchmark models, demonstrating the potential advantages of leveraging transfer learning for odor threshold prediction.

Shifting focus to flavor engineering, our work pioneered a Scientific Machine Learning (SciML) approach, aiming to generate new flavored molecules for application in the flavor industry. The generative framework developed used FlavorDB's database to design several molecules, showcasing the potential of the proposed method.

The research then advanced with the combination of generative and reinforcement learning models to generate new flavor molecules. This framework aimed to identify molecules already available in the market and those requiring further development. Results demonstrated that the proposed deep reinforcement learning method outperformed the deep generative model, emphasizing its efficacy in designing molecules with specific characteristics, as shown in the results presented in Table 1.

Table 1: Designed molecules through deep reinforcement learning assessment results.

| Categories | Number of Molecules | Percentage of Molecules (%) |
|---|---|---|
| Valid molecules | 198 | 99 |
| Invalid molecules | 2 | 1 |
| Existent | 192 | 96 |
| Non-existent | 6 | 3 |
| Used in the flavor industry | 127 | 63.5 |
| Not yet used in the flavor industry | 65 | 32.5 |
| Used in the flavor industry and are in the FlavorDB website database | 101 | 50.5 |
| Used in the flavor industry and are not in the FlavorDB website database | 26 | 13 |
| Not yet used in the flavor industry and are in the FlavorDB website database | 26 | 13 |
| Not yet used in the flavor industry and are not in the FlavorDB website database | 39 | 19.5 |

Furthermore, our work introduced a novel framework for flavor engineering, integrating web scraping, generative, and reinforcement learning in a transfer learning context. This complex system aimed to generate molecules with specific desired characteristics and chemical properties. Results indicated exceptional outcomes, particularly in the transfer learning model's ability to generate molecules within established metrics.

In summary, our research has pioneered frameworks in both perfume and flavor engineering, leveraging the power of Scientific Machine Learning techniques. These methodologies offer innovative approaches to generating molecules with specific characteristics and developing optimal formulations, catering to the evolving demands of these dynamic industries. The proposed models and frameworks have demonstrated promising results, indicating a transformative potential for product engineering in the perfume and flavor sectors.

## Future Perspectives

In future work, the project aims to advance the development of an Artificial Intelligence framework based on a phenomenological model for designing perfumes and flavored molecules, namely focusing on heritage flavor-based products. The outlined tasks include creating a comprehensive database of flavoring molecules through web scraping, conducting in-depth analyses such as cluster analysis and deep generative modeling, and developing predictive models for flavor thresholds. Additionally, the project involves formulating a hybrid model combining an Artificial Neural Network (ANN) with the phenomenological model, contributing to the understanding of physicochemical properties and their impact on flavor molecules. Further efforts will explore optimization through an assessment of European Union regulations and standards, culminating in a final practical application involving the production and flavor analysis of European heritage beverages. Collaboration with experts at various institutions, such as the University College of London Institute for Sustainable Heritage and HFU Business School, ensures a multidisciplinary approach to achieving the project's ambitious objective.

## Related Sustainable Development Goals

## Outputs

**PhD Theses**

[1] Luana Queiroz, Flavor Engineering 5.0: a new approach for design and understanding flavors, PDEQB, FEUP, ongoing.

[2] Luis Oliveira, A cyber-physical prototype for on-demand perfume optimal design and production, PDEQB, FEUP, ongoing.

**Master Dissertations**

[1] Luana Queiroz, Scientific Machine Learning for Product Engineering 4.0, MIEQ, FEUP, 2022.

**Selected Publications**

[1] L.P. Queiroz et al., Industrial and Engineering Chemistry Research, 62, 9062 (2023)

[2] L.P. Queiroz et al., ACS Omega, 8, 10875 (2023)

[3] A L.P. Queiroz et al., Foods, 12, 1147 (2023)

[4] L.M.C Oliveira et al., Heliyon, 9, e20813 (2023)

[5] V.V Santana et al., Computers and Chemical Engineering, 150, 107644 (2021)

## Team

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