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USER CENTRIC SIMULATION OF FOOD PLACEMENT IN HOUSEHOLD REFRIGERATORS

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Keywords

Foods, refrigerator, User, Simulation, ARENA.

Abstract

Household refrigerators operate continuously and constitute a significant share of residential energy consumption, thereby contributing to greenhouse gas emissions. This study examines the combined effects of food placement, user behavior, and food consumption patterns on the thermal energy performance of domestic refrigerators through a simulation-based approach. A two-phase discrete-event simulation model was developed using survey-derived user data and implemented in ARENA. The first phase models food purchasing, storage, retrieval, and consumption dynamics, while the second phase focuses on shelf-level food placement and user interaction within a multi-shelf refrigerator. The results indicate substantial congestion and prolonged waiting times in non-freezer compartments, identifying these zones as critical bottlenecks that increase door-opening durations and thermal loads. High utilization rates and frequent user interactions were found to significantly affect energy efficiency by intensifying compressor operation. The findings demonstrate that systematic and behavior-informed food placement strategies can reduce thermal energy consumption and associated carbon emissions. By integrating food consumption simulation with user behavior

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modeling and refrigerator energy analysis, this study provides a comprehensive and data-driven framework for improving household energy efficiency. The outcomes offer valuable insights for refrigerator design, user awareness, and energy policy development, highlighting the role of micro-level behavioral optimization in achieving broader sustainability and climate mitigation objectives.

EV TİPİ BUZDOLAPLARINDA GIDA YERLEŞİMİNİN KULLANICI ODAKLI SİMÜLASYONU

Anahtar Kelimeler

Gıda ürünleri, Buzdolabı, Kullanıcı, Simülasyon, ARENA

Öz

Ev tipi buzdolapları, konutlardaki toplam enerji tüketiminin önemli bir bölümünü oluşturarak sera gazı emisyonlarını önemli ölçüde arttırmaktadır. Bu çalışma, gıda yerleşimi, kullanıcı davranışı ve gıda tüketim örüntülerinin ev tipi buzdolaplarının ısıl enerji performansı üzerindeki birleşik etkilerini simülasyon temelli bir yaklaşımla incelemektedir. Anket verilerine dayalı kullanıcı girdileri kullanılarak iki aşamalı bir ayrık olay simülasyon modeli geliştirilmiş ve ARENA programı kullanılarak uygulanmıştır. İlk aşamada gıdaların satın alınması, depolanması, buzdolabından alınması ve tüketilmesine ilişkin süreçler modellenmiş; ikinci aşamada ise çok raflı bir buzdolabında raf düzeyinde gıda yerleşimi ve kullanıcı etkileşimleri analiz edilmiştir. Bulgular, dondurucu dışı bölmelerde yüksek yoğunluk ve uzun bekleme süreleri olduğunu, bu durumun kapı açık kalma süresini ve ısıl yükleri artırarak enerji verimliliğini olumsuz etkilediğini göstermektedir. Sonuçlar, davranış temelli gıda yerleşim stratejilerinin enerji tüketimini ve buna bağlı karbon emisyonlarını azaltabileceğini ortaya koymaktadır. Çalışma, kullanıcı davranışı ile enerji analizi bütünleştirilerek hane halkı enerji verimliliğinin artırılmasına yönelik veri temelli ve sürdürülebilir bir çerçeve sunmaktadır.

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1. Introduction

Household refrigerators are substantial contributors to both energy consumption and greenhouse gas emissions, representing a significant area of concern in efforts to combat climate change. The energy consumption of refrigeration systems is intricately linked to the placement of food items within the appliance, which in turn affects thermal loads and overall energy efficiency (Geppert & Stamminger, 2013). Optimizing food placement not only offers potential savings in household energy costs but also presents a viable strategy for reducing carbon footprints, thus contributing to global sustainability goals. In the context of contemporary household appliances, refrigerators stand out due to their continuous operation and substantial energy demands. As global climate control efforts intensify, mitigating waste is critical, especially considering the substantial greenhouse gas emissions associated with food waste management, including its transportation and decomposition. Human intervention plays a crucial role in minimizing food waste, particularly by ensuring that only necessary amounts of food are consumed. This is directly tied to the energy consumption and carbon emissions of household appliances, which are increasingly recognized as pivotal components in global climate change mitigation. Refrigerators, operating round the clock, account for a significant portion of household energy use, yet they remain an underappreciated opportunity for reducing carbon footprints. However, the potential energy savings achievable through strategic food placement and efficient thermal management within these appliances remain critically understudied.

The energy consumption of refrigerators is influenced by various factors, including thermal loads imposed by food items, ambient temperature, and user behavior such as the frequency of door openings (Joybari, Hatamipour, Rahimi & Modarres, 2015). Research has shown that improper food placement can lead to inefficient cooling and increased energy use. For instance, energy consumption can rise by up to 10% when refrigerator temperatures fluctuate due to frequent door openings (Susanto, Pranoto & Nugroho, 2018). Optimizing food placement is therefore essential for maintaining consistent internal temperatures and reducing energy costs. The link between thermal energy costs and carbon footprints is significant, as higher energy consumption correlates directly with greater greenhouse gas emissions. Promoting energy-efficient appliances, such as refrigerators, is crucial for achieving carbon neutrality goals (Lv & Zhang, 2023). By strategically optimizing food placement, households can decrease their energy consumption and thus lower their carbon footprints.

Food consumption is influenced not only by economic factors but also by a wide range of complex elements such as cultural practices, social interactions, psychological drivers, and individual preferences. Existing simulations often struggle to adequately capture this complexity. Consumer behavior can evolve over time and simulations need to better model dynamic behavioral changes, such as the effects of new product introductions or increasing health consciousness on consumption patterns. Insights from behavioral economics and psychology can be integrated into food consumption simulations. Climate change scenarios and sustainability indicators can be incorporated to assess potential future risks and opportunities. Multi-agent modeling approaches can be employed to better understand interactions among food system actors (e.g., producers, consumers, retailers). Simulations must consider the consumption habits and trends of population growth, aging, and urbanization have profound impacts on food consumption. It is crucial that simulations forecast how these demographic shifts may influence future food demand.

Recent technological advancements, such as the integration of phase change materials, have shown promise in enhancing energy efficiency by stabilizing internal temperatures, reducing compressor cycling, and ultimately decreasing energy usage (Maiorino, Duca, Mota-Babiloni, & Palmieri, 2019). Furthermore, adaptive model predictive control techniques can optimize refrigerator operation based on real-time data related to food placement and thermal loads, offering another avenue for significant energy savings (Bálint, Fodor & Hangos, 2017). These innovations underscore the potential for combining technological advancements with user behavior to achieve substantial energy reductions. Additionally, the investigation of user perceptions and habits regarding refrigerator use, specifically concerning food placement optimization and energy factors, represents a gap in the existing literature. It is crucial to develop new, energy-efficient food placement strategies by quantifying and analyzing user habits during interactions with refrigerators. The modeling of food consumption patterns and refrigerator usage behaviors will be central to designing more efficient food placement plans. A lack of reliable and up-to-date data on food consumption can undermine the accuracy and credibility of simulations. This problem is especially pronounced in developing countries. Integrating diverse data sources like to consumption surveys, agricultural production data, and demographic statistics is essential to enhance the validity of simulation models.

Climate change directly affects agricultural production and food supply. Simulations should incorporate how environmental changes such as drought or water scarcity may alter consumption patterns. Food production and consumption have important implications for environmental sustainability. It is important for simulations to evaluate the environmental impacts of different consumption scenarios, including greenhouse gas emissions and water usage. The broader implications of this research extend far beyond individual households. As global climate change accelerates and energy resources become more limited, even marginal improvements in household energy efficiency can contribute significantly to global sustainability objectives. By providing data-driven insights into optimizing refrigerator thermal dynamics, this study aims to empower consumers with actionable strategies to reduce their carbon emissions, one strategic food placement at a time. In an era marked by rising energy costs and increasing environmental awareness, household refrigerators occupy a critical intersection between daily user interaction and energy consumption. While essential for modern living, refrigerators represent a significant proportion of household energy use, with efficiency largely influenced by user behavior and operational patterns. Understanding the complex relationship between user interaction and energy consumption is key to both environmental sustainability and economic efficiency. Despite technological advances in refrigeration that have improved baseline efficiency, actual energy consumption often deviates from manufacturer estimates due to various user behavior factors. The interplay between user experience parameters and energy consumption offers a unique opportunity for optimization. This paper focuses on the optimization of food placement within refrigerators as a means of reducing thermal energy costs and minimizing carbon footprints. The central hypothesis posits that systematic food arrangement within refrigerators can significantly reduce thermal load, minimize energy consumption, and ultimately lower the carbon footprint of domestic refrigeration. Given that household refrigerators account for approximately 7% of total electricity demand in the U.S. Department of Energy, optimizing food placement can lead to significant reductions in energy consumption and associated carbon emissions. Through this analysis, we explore how intelligent food placement strategies can alleviate thermal energy costs and simulate the users' behaviors while advancing sustainability goals. Food consumption plays a critical role in reducing carbon footprints as an integral component of environmental sustainability. The production, transportation, storage, and consumption of food have significant environmental impacts. In this context, food consumption simulations, carbon footprint calculations, and research into energy-efficient refrigerator designs contribute to the adoption of a more sustainable lifestyle. While food consumption simulations are valuable tools for calculating carbon footprints, the role of refrigerator designs in enhancing energy efficiency remains critical. However, the existing literature does not adequately address the integrated effects of these factors, warranting further research into their combined influence on energy use and environmental impact.

2. Literature Review

The energy consumption of refrigerators is influenced by a range of factors, including ambient temperature, food load, and door openings (Geppert & Stamminger, 2013). Research has shown that improper food placement can result in increased energy usage due to inefficient cooling. For example, ambient temperature plays a significant role in energy consumption, with higher temperatures demanding more energy from the refrigeration system to maintain internal cooling (Geppert & Stamminger, 2013). Similarly, the thermal load from food items can have a considerable impact on energy efficiency. Improper food placement can cause temperature fluctuations that force the compressor to work harder, leading to higher energy consumption (Martínez-Martínez, Valero, Carrasco & Llorens-Ivorra, 2023). Despite considerable advancements in refrigerator design and energy efficiency, several critical areas remain underexplored. Notably, the quantitative relationship between user experience parameters and energy consumption, the influence of ergonomic factors on daily energy usage patterns, and the integration of user behavior with energy optimization strategies have not been sufficiently examined. While previous studies have separately explored user behavior or energy efficiency, the intersection of these factors remains a largely unexplored domain. Understanding how visual comfort, reachability, and user interaction patterns influence energy consumption could lead to more efficient design solutions and usage guidelines. The relationship between thermal energy costs and carbon footprints is particularly important, as higher energy consumption due to inefficient refrigeration practices directly correlates with increased carbon emissions. For instance, the adoption of CO_2 refrigerants in cascade systems has been shown to enhance energy efficiency compared to traditional systems, thus reducing the overall CO_2 emissions associated with refrigeration (Yamaguchi, 2017). Additionally, optimizing food placement within refrigerators can lower energy consumption, which in turn reduces the carbon footprint associated with food storage (Tassou, Lewis, Ge, Hadawey & Chaer, 2010).

Emerging technologies and strategies hold significant promise in optimizing food placement in refrigerators. The integration of phase change materials is one such advancement, stabilizing internal temperatures and reducing the energy required for cooling (Raveendran, Sekhar & Radhakrishnan, 2021). Furthermore, model predictive control systems can manage refrigerator operations based on real-time data about food placement and thermal loads, leading to improved energy efficiency (Sabegh & Bingham, 2019). These innovations emphasize the potential for combining technological advancements with user behavior to achieve substantial energy savings. In terms of food placement optimization, several studies have employed advanced mathematical models to identify the best strategies. For instance, a convex linear optimization problem was solved using the Mixed Integer Programming (MIP) method to determine optimal food placement in household refrigerators. Various studies have been synthesized to define the underlying methodology for this approach. For example, a study focused on cost-performance maximization, shelf optimization, and minimizing walking distances in the context of increased production demand, employing a greedy algorithm (Özçelik & Gündüz, 2019). Similarly, planogram software, which organizes shelf and product placement, was used to generate optimized placement diagrams, applying constraints based on product order, dimensions, and optimization rules.

Another study optimized supermarket shelf placements through part-feeding activities and picking operations, similar to those in automotive manufacturing (Zangaro, Battini, Calzavara, Persona & Sgarbossa, 2018). Additionally, linear programming models have been used to optimize warehouse energy expenditure, further emphasizing the application of mathematical models for optimizing space and energy use in storage systems (Diefenbach & Glock, 2019). These studies illustrate the broad applicability of optimization techniques in solving real-world problems in various industries.

In the context of household refrigerators, the present study evaluates refrigerators with different energy efficiency classes and designs, calculating their energy consumption costs. Constraints related to user experiences such as reachability and visual comfort are incorporated into the mathematical model. The motion trajectory regression equations and additional constraints were derived by Park, Kim & You (2011). Additionally, refrigerator energy consumption equations based on food load (kg) and ambient temperature from previous study by Belman-Flores, Pardo-Cely, Gómez-Martínez, Hernández-Pérez, Rodríguez-Valderrama & Heredia-Aricapa (2019) were used to calculate the lowest annual energy consumption costs.

Food consumption simulations have emerged as important tools for evaluating the environmental impacts of food choices. These models calculate the effects of dietary habits on various environmental parameters, such as greenhouse gas emissions, water use, and land use. These simulations also help promote sustainable food choices by calculating the carbon footprint of food consumption. Poore & Nemecek (2018) examined the most effective food choices for reducing carbon footprints by modeling the environmental impacts of food production and consumption. Their study emphasized avoiding foods with high carbon footprints, such as red meat and dairy products. Similarly, Springmann Godfray, Rayner & Scarborough (2016) simulated the environmental impacts of dietary changes in the UK, highlighting the benefits of adopting more plant-based diets for reducing carbon footprints.

However, several gaps remain in the literature regarding food consumption simulations. Much of the existing research relies on theoretical studies of specific diets or food groups, without considering the real-world context of food choices. Furthermore, there is limited research on the applicability of individual and societal behavioral changes to reduce environmental impacts. While refrigerator designs have focused primarily on energy efficiency, there is a need for more research on the role of user habits and psychological factors in energy use. Additionally, the potential for integrating smart refrigerators and food consumption simulations to reduce carbon footprints warrants further exploration. Although current studies on refrigerator design emphasize energy efficiency, they often overlook user behavior under real-world conditions, which could significantly impact energy consumption and sustainability outcomes. In conclusion, further research is needed to address these gaps, particularly regarding the integration of food consumption simulations, refrigerator design, and user behavior. The combined effects of these factors on sustainability remain insufficiently explored, and more data collection and modeling are required to enhance our understanding of their impact on reducing carbon footprints and energy consumption.

3. Simulation of Food Consumption

A quantitative and computational approach for modeling how food products are selected, stored, consumed, and wasted over time under varying environmental, behavioral, and operational conditions can be constituted by simulation. In an academic context, this simulation framework integrates user behavior models, demand variability, and temporal consumption patterns with system-level parameters such as storage capacity, thermal conditions, and replenishment cycles. By employing techniques including discrete-event simulation, agent-based modeling, or system dynamics, food consumption simulation enables researchers to analyze complex interactions between consumers and food systems in a controlled, reproducible environment. The approach is particularly valuable for evaluating scenarios related to energy efficiency, sustainability, and food waste reduction, as it allows for sensitivity analysis and policy testing without the cost and uncertainty of real-world experimentation. Consequently, food consumption simulation serves as a robust decision-support tool for optimizing household and industrial food management strategies while supporting data-driven insights into sustainable consumption behaviors. The study by Karabacak (2022), aimed at modeling refrigerator users' food product consumption behavior through simulation, survey results based on food products and a 10-shelves refrigerator model were utilized. The simulation was implemented using the ARENA program. The simulation consisted of two phases: firstly, a general consumption simulation, and secondly, a shelf usage simulation. In the first phase which is in Figure 1, refrigerators with two shelves in the freezer compartment were examined, assuming one of the shelves was used at a frequency of every three days.

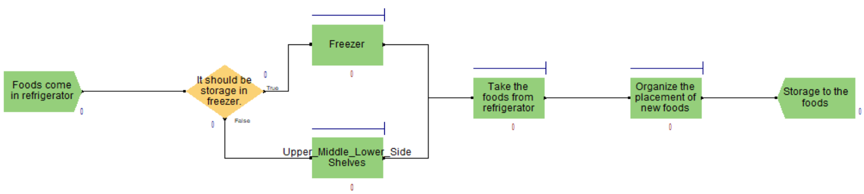

Figure 1. Flow Diagram of Phase 1 Simulation Model for Refrigerator Food Storage Behavior, simulates periodic food placement, storage, retrieval, and consumption activities based on user interaction patterns.

The remaining sections of the refrigerator were treated as a single unit. According to the survey results, foods are typically purchased and stored in the refrigerator approximately every 10 days. After the foods are placed in the refrigerator, the storage process begins, followed by the retrieval and consumption of the foods. It was assumed that the time spent for food retrieval and consumption was equally divided. According to the survey, these processes occur approximately every three days. The maximum reported purchase frequency in the survey was 12 days. The survey considered the monthly purchase of food products. The simulation of the food product storage system in the refrigerator was planned to run for 240 min. as an example. According to the survey results, the inter-arrival time of foods arriving for storage in a refrigerator is EXPO(2) minutes. 36% of the arriving foods are placed in the freezer compartment, while the rest are placed in the non-freezer compartments. A user places the foods in the freezer compartment, and this process takes TRIA(1,2,3) minutes. A user places the foods in the non-freezer compartments, and this process takes EXPO(4) minutes. After the foods are retrieved from the refrigerator, new foods with different characteristics are placed in the same refrigerator. The time spent for retrieving and placing foods in the refrigerator is equal. First, the foods are retrieved from the refrigerator, and this process takes EXPO(1) minutes. The time spent for placing the foods is TRIA(1,2,3) minutes. This information was obtained from the input analysis of the data obtained from the survey in the ARENA program. The aim is to determine the average and maximum waiting time in the queue for all formed queues, the average and maximum number of foods waiting in the queue for each queue, and to find the utilization rates of the freezer and non-freezer compartments of the refrigerator. The second phase which is in Figure 2 was conducted for one day, considering the placement and retrieval of food products from shelves and an exemplary user behavior, assuming that products could be placed on a lower shelf sequentially. As a result, the simulation continued until all food products were consumed.

Figure 2. Simulation of Food Placement and Retrieval in a 10-Shelf Refrigerator Using Beta Distribution, represents typical user behavior for product allocation and shelf access within a one-day cycle.

The sample refrigerator brand M11 was chosen for second phase simulation in study Karabacak (2022). Users of the M11 brand 10-shelves refrigerator purchase products approximately 29 times per month. Monthly arrivals occur an average of 35 times for each user, with an average of 1.16 arrivals per day. Average arrival values for refrigerator compartments were calculated. The waiting time of the compartment with the higher arrival value was considered. Food arrivals for the M11 brand 10-shelves refrigerator follow a Beta distribution in Figure 3. This study was conducted in accordance with the principles of research and publication ethics.

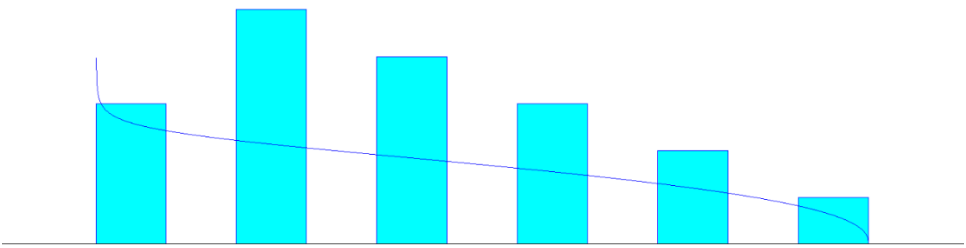

Figure 3. Arrival Distribution of Food Items in a 10-Shelf Refrigerator (Brand M11) Based on Monthly Purchase Frequency, simulated arrival pattern follows a Beta distribution derived from user survey data.

4. Simulation Results

Following the model setup, the simulation was executed, and upon completion, the system's operational reports were generated by the program. The average, minimum, and maximum waiting times for all formed queues were determined. The first phase simulation results were given in Appendix-1. According to the results of the first phase, 0.47-min. queue was observed for food retrieval from the refrigerator within 240-min. timeframe. The waiting time for foods in the non-freezer compartment was 37.85 min., while it was 0.39 min. for foods in the freezer compartment. 2.38-min. queue was observed during the organization of new food item placements. These results indicate a continuous queue formation due to waiting foods in the non-freezer compartment, which is identified as a critical bottleneck activity. The average and maximum number of food items waiting in each queue were also determined. In the non-freezer compartment, 10 food items waited externally, forming a queue.

The maximum number of food items in the queue being 18 and the user's time expenditure percentage being 99% suggest the necessity for an arrangement in the non-freezer compartment. According to the results, 115 food items are within the system for a single user. In the second phase, a one-day simulation showed an average of 666 food items present in the refrigerator and 46 food items undergoing processing. The utilization rate of the non-freezer compartments was 98%. 39% of food items are retrieved from the refrigerator within 24 hours, and 82% of food item placements are organized by users. The second phase simulation results were given in Appendix-2. Table 1 shows the summarized simulation results of food consumption.

Table 1.

Simulation Results

Simulation Phase	Performance Metric	Non-Freezer Compartment	Freezer Compartment	Remarks
Phase 1 (240 min)	Average waiting time (min)	37.85	0.39	Non-freezer section identified as critical bottleneck
	Maximum waiting time (min)	—	—	Queue persistence observed in non-freezer area
	Queue length (average)	10 items	—	External queue formation detected
	Queue length (maximum)	18 items	—	Indicates congestion and saturation
	Queue during food retrieval (min)	0.47	—	Observed within 240-minute timeframe
	Queue during food placement (min)	2.38	—	Organization activity causes delay
	User time utilization (%)	99%	—	High workload concentration
	Total food items in system	115 items	—	Single-user scenario
Phase 2 (24 hours)	Average food items in system	666 items	—	Daily interaction intensity
	Food items under processing	46 items	—	Active user interaction
	Compartment utilization rate (%)	98%	—	Near-capacity operation
	Food retrieval within 24 hours (%)	39%	—	High access frequency
	User-organized placements (%)	82%	—	Strong behavioral influence

The results obtained from the ARENA simulation model offer significant insights into user behavior and its implications for energy efficiency in household refrigeration. Specifically, the prolonged waiting times and high queue formation in the non-freezer compartments indicate a systemic inefficiency in how users currently organize and access stored food. This suggests that non-freezer areas are critical bottlenecks, where poor food organization leads to increased door-open durations and thus higher thermal loads. The findings from the ARENA-based simulation, as illustrated in Figures 1–3 and model results are in Appendix-1, offer several key insights into the thermal dynamics and behavioral inefficiencies associated with food placement in household refrigerators. First, the average waiting time of 37.85 minutes for food items in the non-freezer compartment in contrast to only 0.39 minutes in the freezer compartment indicates a critical bottleneck in refrigerator usage. This suggests that food items in non-freezer sections are more frequently accessed, leading to longer door opening durations, which increase internal temperatures and force the compressor to compensate, thereby raising energy consumption. Additionally, the queue size of up to 18 food items in non-freezer areas and a compartment utilization rate of 98% point to a saturation problem. From a design and behavioral perspective, this high congestion implies that users may be unintentionally contributing to inefficient energy usage by overloading accessible compartments rather than distributing items according to optimal thermal zoning. In the second phase of the simulation, the daily average of 666 food items in storage and 46 items undergoing active processing further reinforces the intense level of interaction users have with refrigerator interiors. The fact that 82% of placement tasks are manually performed and 39% of food items are retrieved within 24 hours highlights a strong behavioral pattern that could be used to design predictive control algorithms or dynamic shelf reallocation strategies. Most importantly, the simulation quantifies these behavioral patterns in a way that demonstrates their direct correlation with energy inefficiency. For example, long queue durations and repeated access to certain compartments suggest the need for zoned cooling systems, where more frequently used areas are more responsive to rapid temperature recovery, smart layout suggestions via digital interfaces, or even automated reorganization features in next-generation refrigerators. Thus, these results are not merely descriptive but have clear design, engineering, and policy implications. They provide empirical backing for the development of behavior-informed refrigeration systems and underscore the potential of micro-level user actions to impact macro-level energy outcomes.

5. Discussion

The actionable information of results provides guidance for designers, awareness for users, and concrete suggestions for energy policies. Refrigerators store a wide variety of food products (e.g., meat, dairy, vegetables, fruits, cooked meals), each with unique physical and chemical properties, such as thermal conductivity, moisture content, and spoilage rates. Simulations need to incorporate detailed models that reflect these differences. Packaging significantly influences heat and moisture transfer, thereby affecting the shelf life of food items. Simulations should account for the impact of different packaging materials (e.g., plastic containers, glass jars, cling film) on food preservation. A wide range of refrigerator designs exist in the market (e.g., single-door, double-door, no-frost systems), each with unique airflow patterns and temperature distributions. Simulations should include customized models that reflect these structural and functional differences. Factors such as ambient temperature, door opening frequency, and food load significantly influence internal temperature distribution and food shelf life. Simulations must model the effects of these operating conditions for more accurate predictions.

The arrangement of food within the refrigerator affects temperature distribution, which in turn impacts food safety and shelf life. Simulations can be used to test different placement strategies (e.g., placing perishable items in the coldest zone) and develop optimal configurations. Incorporating consumer habits such as how long the refrigerator door remains open or how users typically arrange food can enhance the realism and accuracy of simulations. The refrigerator's energy use is affected by variables such as food quantity, placement, and operating conditions. Simulations can explore how different food placement strategies impact energy consumption and provide recommendations for improving energy efficiency. Advanced thermal modeling techniques are required to accurately simulate temperature distributions within the refrigerator. Computational fluid dynamics methods can be used to analyze airflow and temperature patterns in greater detail, enabling more precise simulations. To ensure simulation reliability, empirical validation using experimental data is essential.

6. Conclusion

This study highlights the critical role of food placement within household refrigerators in reducing thermal energy consumption according to simulation results. Users often place food items in areas that are difficult to access or see, particularly in the rear parts of the refrigerator. The findings suggest that layout plans optimized for food placement can significantly reduce energy consumption, contributing to both energy savings and better management of the energy crisis, especially in countries aiming for sustainable design. This approach presents a practical and cost-effective solution to enhance sustainability in household refrigeration systems. Additionally, these energy savings can benefit both consumers by reducing costs and energy companies by increasing operational efficiency. It emphasizes the importance of food placement not only in terms of reducing energy costs but also in supporting sustainable development. This research provides an offering a strategy that could be applied globally to improve refrigerator design and user behavior. The results can guide future refrigerator designs that integrate both user experience and energy efficiency, promoting sustainable practices in domestic environments. The integration of refrigerator design and food consumption simulations presents a more comprehensive approach to reducing the carbon footprint of household refrigeration. This dual focus allows for more effective energy management and reduces waste by considering both food storage needs and energy usage. Despite significant progress in food consumption simulations, the literature remains limited, particularly when considering the complexity of real-world consumer behavior, cultural preferences, and environmental variations.

Encouraging interdisciplinary collaboration among experts in food science, engineering, and computer science. Employing big data analytics and machine learning techniques to enhance model complexity and accuracy. Integrating Virtual Reality (VR) and Augmented Reality (AR) technologies into simulation systems for more interactive and immersive analysis. Developing integrated simulation systems compatible with smart refrigerators to support real-time monitoring and decision-making. Future research should address these gaps by developing dynamic and heterogeneous models that reflect the complexities of consumer preferences, health outcomes, and environmental impacts. Additionally, the incorporation of advanced technologies, such as Artificial Intelligence (AI) and big data analytics, into these simulations is still in its early stages. Expanding the integration of these technologies could provide more accurate and scalable solutions for optimizing food consumption and refrigeration systems. By optimizing both food placement and refrigerator design, it is possible to reduce energy consumption, minimize food waste, and lower carbon footprints. However, the current body of research often focuses on theoretical models, overlooking real-world complexities such as user behavior and cultural differences. Future studies should explore these aspects more deeply, creating practical, user-friendly solutions that integrate innovative technologies and behavioral insights. Through this holistic approach, energy-efficient systems contributing to the broader goal of environmental sustainability can be created to socities and nature.

Contributions of Author

Nimet KARABACAK contributed to the literature review, performed data collection from her doctoral dissertation, statistical analyses; developed the methodology; implemented the simulation model; interpreted the results; and wrote the original draft and final version of the manuscript. Ilgın ACAR contributed to the design of the questionnaire and provided academic supervision throughout the research process. Engin KAPKIN contributed to the design of the questionnaire and provided academic supervision.

Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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