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# Efficiency loss of household refrigeration appliances over time and associated impacts: Dynamic modelling of operational features and life-cycle

**Institut für Landtechnik**

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# Efficiency loss of household refrigeration appliances over time and associated impacts: Dynamic modelling of operational features and life-cycle

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von

**Christian Hüppe**

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# Abstract

**Efficiency loss of household refrigeration appliances over time and associated impacts: Dynamic modelling of operational features and life-cycle**

Nowadays, household refrigeration appliances belong to the standard equipment of most homes. Since refrigerators, freezers and refrigerator-freezer combinations generally operate continuously throughout their service life, they range among the largest energy users in the residential sector. As a consequence, policies were established and revised over time to improve refrigeration appliance's efficiency and decrease their environmental impacts. However, certain characteristics, such as the efficiency loss over time were largely disregarded by previous research and, consequently, its impact on appliance's energy consumption is yet unknown. Although operational features, i.e. the daily consumer interactions with refrigeration appliances, were monitored in the past their influence was similarly neglected. Therefore, this thesis followed two main objectives in order to close this research gap.

At first, the age-related efficiency loss over time was investigated. A range of new appliances was acquired and divided in test groups. One test group was exposed to fluctuating temperatures over the course of two years, whereas the other group was placed under constant ambient conditions. A non-destructive testing method (*Bonn method*) was developed to investigate the degrading insulation performance over time and applied in parallel to energy consumption measurements to all sample appliances. This way, both changes in insulation properties and consumption patterns were evaluated. Second, a static energy model was extended to a dynamic approach by including changes in efficiency over time. The consumer behaviour was surveyed by a national questionnaire and served as input for the dynamic model to evaluate the impact of behaviour on appliance's energy consumption. A list of advice (*best practices*) on the correct handling of refrigeration appliances was compiled and applied to the dynamic model. The comparison between the real-life consumer behaviour and the *best practices* determined the share of behaviour in appliance's energy consumption. At last, the investigated efficiency loss was implemented to a life-cycle assessment to estimate environmental impacts and monetary losses resulting from the degrading efficiency throughout the life-cycles of refrigeration appliances.

# Kurzzusammenfassung


**Effizienzverlust von Haushaltskühlgeräten während der Nutzungszeit und dessen Auswirkungen: Eine dynamische Modellierung von Betriebsmerkmalen und Lebenszyklus**

Haushaltskühlgeräte gehören heutzutage zur Standardausstattung von privaten Haushalten und werden in der Regel ihre gesamte Nutzungszeit über unterbrechungsfrei betrieben. Aus diesem Grund gehören Kühlgeräte zu den energieintensivsten Haushaltsgeräten und sind durch zahlreicher Maßnahmen adressiert worden. Diese hatten die Effizienzerhöhung und eine gleichzeitige Minimierung negativer Umwelteinflüsse zum Ziel. Jedoch blieben bestimmte Eigenschaften, wie der Effizienzverlust während der Nutzungszeit, in vorangegangenen Maßnahmen unberücksichtigt und sind in früherer Forschung nicht fokussiert worden. Daher ist der alterungsbedingte Effizienzverlust von Haushaltskühlgeräten weitgehend unbekannt. In ähnlicher Weise sind Betriebsmerkmale, d.h. die Nutzung durch den Verbraucher, zwar untersucht worden, ihr langfristiger Einfluss auf den Energieverbrauch aber nur unzureichend bekannt. Die vorliegende Dissertation verfolgt zwei Hauptziele, um diese Forschungslücke zu schließen.

Zu Beginn der Studie lag der Fokus auf der Untersuchung des alterungsbedingten Effizienzverlustes. Haushaltskühlgeräte sind in Testgruppen eingeteilt und während des Untersuchungszeitraums unterschiedlichen Umgebungsbedingungen ausgesetzt worden. Eine zerstörungsfreie Testmethode (*Bonn method*) bzgl. der Isoliereigenschaften ist entwickelt und neben Energieverbrauchsmessungen regelmäßig auf alle Untersuchungsgeräte angewandt worden. Somit wurden Veränderungen der Isolationseigenschaften und des Energieverbrauchs im Zeitverlauf evaluiert. Ein weiterer Fokus lag auf der Dynamisierung eines statischen Energieverbrauchmodells. Das Verbraucherverhalten ist in einer deutschlandweiten Onlineumfrage untersucht und als Input im dynamischen Modell eingepflegt worden. Eine Liste zum energieeffizienten Verbraucherverhalten (*best practices*) wurde aufgestellt und der Output mit dem der realen Verbraucherinformationen verglichen. Auf diese Weise konnten Verhaltenseinflüsse auf den Energieverbrauch bestimmt werden. Schließlich ist der Effizienzverlust in eine Lebenszyklusanalyse integriert worden, um die Auswirkungen der Degeneration von Haushaltskühlgeräten auf die Umwelt und Wirtschaft zu evaluieren.

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# Nomenclature (list of abbreviations)

| General abbreviations: | |
|---|---|
| $EC$ | Energy consumption |
| $Rf$ | Refrigerator |
| $Fr$ | Freezer |
| $RFC$ | Refrigerator-freezer combination |
| $PUR$ | Polyurethane foam insulation |
| $T_a$ | Ambient temperature (in °C) |
| $T_{in}$ | Internal compartment temperature (in °C) |
| $TA$ | Test appliances: appliances exposed to dynamic temperature changes |
| $RA$ | Reference appliances: appliances exposed to constant temperatures |
| $\lambda$ | Thermal conductivity (in $\mathrm{W/m * K}$) |
| $\lambda_{PUR}$ | Thermal conductivity of $PUR$ (in $\mathrm{W/m * K}$) |
| $k$ | Heat transfer coefficient (in $\mathrm{W/m^2 * K}$) |
| $Bonn\ method$ | Non-destructive test method to determine insulation properties |
| $\tau_I$ | Test value of the $Bonn\ method$ (in $\mathrm{min^{-1}}$) |
| $p$ | Pressure |
| $GHG$ | Greenhouse gas emissions |
| $ODP$ | Ozone depletion potential |
| $CFC$ | Chlorofluorocarbons |
| $EoL$ | End-of-life: Closing stage in a life-cycle assessment |
| $POC$ | Persistent organic compounds |
| $VOC$ | Volatile organic compounds |
| $DUB$ | Direct using behaviour in the interaction with refrigeration appliances |
| $IUB$ | Indirect using behaviour in the interaction with refrigeration appliances |
| $Q$ | Question (especially used in the survey context) |
| **Dynamic energy model** | |
| $n_{door\_opening}$ | Total number of refrigeration appliance door openings (per day) |
| $n_{food\_frequ}$ | Frequency of warm food storages (per year) |
| $n_{food}$ | Total number of food portions stored in an appliance (per storage) |
| $n_{bev}$ | Total amount of beverages stored in an appliance (in litres per week) |
| $P_{off}$ | Stand-by power consumption (in W) |
| $t_i$ | Hours of a year $i$ (assumed to be constant, 8760h) |
| $\varepsilon$ | Impact of external heating sources on the $EC$ (in %) |
| $\eta^*$ | Efficiency factor (in $\mathrm{W/K}$) |
| $a$ | Substitution factor |
| $Q_{input\_i}$ | Consumer heat input in year $i$ (in Wh) |

| | |
|---|---|
| $d_\lambda$ | Temperature-dependent degradation (factor) |
| $d_\lambda^{cc}$ | Annual insulation degradation under a given thermal load (in %) |
| $g_i$ | Ageing-based degradation (factor) |
| $T_a^c$ | $T_a$ at the installation site of a consumer household (in K) |
| $T_{a\_max}^c$ | Maximum $T_a^c$ at the installation site of a consumer household (in K) |
| $x$ | Temperature difference between the $T_a^c$ and the condenser surface (in K) |
| $y$ | Temperature difference between the $T_a^c$ and the evaporator surface (in K) |
| $\alpha$ | Weighting factor (in %) |
| $TL$ | Total thermal load |
| $DF$ | Attenuation factor |
| $V_{net}$ | Net volume of a household refrigeration appliance (in $m^3$) |
| **Subscripts** | |
| $i$ | Year of interest ($i \in 1, \dots, n$) |
| $d$ | Door, indication for door openings |
| $f$ | Food, indication for food storage |
| $b$ | Beverages, indication for the storage of beverages |
| $c$ | Denoting an installation site (e.g. at a consumer household) |
| $pc$ | regional weather condition in the postcode region of a consumer |
| The nomenclature lists the most frequently used abbreviations. Definitions or abbreviations that were seldom used are not listed in the nomenclature. | |

# List of equations