Institut für Landtechnik
Professur für Haushalts- und Verfahrenstechnik
Prof. Dr. rer. nat. Rainer Stamminger

Modelling of domestic refrigerators’ energy consumption under real life conditions in Europe

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Abstract

Modelling of refrigerators' energy consumption under real life conditions in Europe

In recent decades, energy and resource savings have become increasingly important, not only in the industrial, but also the residential sector.

As one of the largest energy users in private homes, domestic refrigerators and freezers were among the first appliances to be targeted for energy efficiency improvements. With the aim of encouraging manufacturers to develop and produce more efficient appliances, the European Energy Label was introduced in the mid-nineties. However, the energy use of refrigerators does not only depend on technical components and features. Especially the using conditions in private homes are of a decisive influence.

Thus, the present study has been conducted to test the sensitivity of refrigerators' energy consumption to various usage conditions within realistic ranges, which have been determined by means of two empirical studies. Key information gathered from the experiments were used as a base for the development and validation of a simplified model that allows predicting the energy consumption of refrigerators in use.

The practical experiments were performed under controlled laboratory conditions with four different refrigerators with an A^+ or A^{++} energy efficiency rating (two statically cooled built-in fridge-freezers, one dynamically cooled refrigerator and one statically cooled refrigerator). The investigations revealed that the ambient temperature has the greatest impact on a refrigerator's energy consumption, followed by thermostat setting and heat load by insertion of warm items. The refrigerators' load under static conditions as well as the number of door openings have almost no impact on energy consumption.

The modelling methodology follows a first-principle approach adjusted by experimental data. When compared to experimental results, model predictions show a reasonable agreement for the whole range of investigated conditions.

Kurzfassung

Modellierung des Energieverbrauchs von Kühlgeräten unter verbrauchernahen Bedingungen in Europa

In den letzten Jahrzehnten haben die Themen Energie- und Ressourceneinsparung sowohl im Industrie- als auch im Wohnbereich immer mehr an Bedeutung gewonnen. Zu den größten Energieverbrauchern im Privathaushalt zählen Kühl- und Gefriergeräte. Daher gab und gibt es Anstrengungen, die Energieeffizienz dieser Geräte zu verbessern. Mitte der Neunziger Jahre wurde das EU-Energie-Etikett für Kühl-und Gefriergeräte unter anderem mit dem Ziel eingeführt, die Entwicklung und Produktion effizienterer Geräte seitens der Hersteller durch Wettbewerbsvergrößerung voranzutreiben. Der Energieverbrauch der Geräte ist jedoch nicht nur von den eingebauten technischen Komponenten und der Bauart abhängig, sondern wird entscheidend von der jeweiligen Nutzung beeinflusst.

Daher war es Ziel der vorliegenden Arbeit, den Einfluss verschiedener Nutzungsfaktoren auf den Energieverbrauch von Kühlgeräten innerhalb realistischer Grenzen zu testen, die mittels zwei empirischer Studien ermittelt wurden. Auf Grundlage der experimentellen Daten wurde ein Modell entwickelt und validiert, welches die Vorausberechnung des Energieverbrauchs von Kühlgeräten in Nutzung ermöglicht.

Die Laborexperimente wurden unter kontrollierten Bedingungen mit vier verschiedenen Geräten der Energieeffizienzklasse A^+ und A^{++} (zwei statisch gekühlte Einbau-Kühl-Gefrier-Kombinationen und jeweils ein Kühlgerät mit dynamischer und statischer Kühlung) durchgeführt. Es zeigte sich, dass die Umgebungstemperatur den weitaus größten Einfluss auf den Energieverbrauch von Kühlgeräten ausübt, gefolgt von der Innentemperatureinstellung und dem Wärmeeintrag durch Lebensmittel. Der Einfluss von Befüllungsgrad unter sonst statischen Bedingungen sowie von Türöffnungen ist hingegen als gering zu bewerten.

Der Modellansatz basiert auf thermodynamischen Grundlagen und wurde mit Hilfe experimenteller Daten angepasst. Ein Vergleich der vorausberechneten Energieverbräuche mit den gemessenen Werten zeigt eine gute Übereinstimmung für den gesamten untersuchten Bereich.

Content

Acknowledgements

Curriculum Vitae

1 Introduction

In the 27 member countries of the European Union, the residential sector is one of the largest energy consumers. This sector represents more than one quarter of total energy consumption [EUROSTAT, 2011]. Cooling appliances like refrigerators and freezers have a substantial share in the residential electricity use. In contrast to other domestic appliances they have to operate permanently. Moreover, these appliances are almost common in every European household. With an average saturation of 106 % the European market for refrigerators and fridge-freezers is already oversaturated. Freezers show penetration rates of about 52 % for EU-15 [STAMMINGER, 2001].

As one of the largest energy users in private homes, cooling appliances have become a target for energy efficiency improvements. In Europe, the European Energy Label was introduced in mid-nineties with the aim of encouraging manufacturers to develop and produce more efficient appliances. A further objective of the Label is to eliminate the least efficient devices from the market by animating consumers to buy and use only the most efficient ones.

Refrigerators' energy consumption depends on a large number of factors. Besides of technical components like the cooling volume, the insulation, the compressor, the condenser and the evaporator, the way of handling it and the ambient conditions have a decisive influence. Especially the factors ambient temperature, internal temperature, frequency of door openings, degree of filling and placement of warm products are of particular importance.

Currently, the last mentioned factors are widely disregarded in European Energy Label test for domestic refrigerators. During this test, the fresh food compartment is empty, the doors remain closed and the ambient temperature is set at 25 °C. These conditions are artificial and seldom reflect the consumers' real life behaviour and conditions. Accordingly, this is a frequent point of criticism.

To date, investigations on the impact of different ambient and handling factors on refrigerators' energy consumption covering the entire consumer relevant area are lacking. Based on a series of own empirical and experimental investigations, this work shall make a contribution to quantify the influences of these factors and to predict real life energy consumption of refrigerators in private homes.

2 Theoretical background

2.1 Energy consumption in Europe

Along with the industry and transport sector, the residential sector belongs to the largest energy consumers in Europe. This sector represented more than one quarter of final energy consumption (25.4 % of total energy consumption, based on tonnes of oil equivalent) in EU-27 in 2008 (cf. Figure 2-1). [EUROSTAT, 2011]. The European Environment Agency [2001] even stated a share of 29 % in the countries of the European Economic Area (EEA).

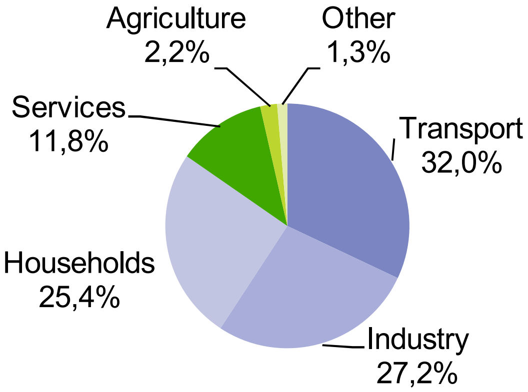

Figure 2-1: Final energy consumption in EU-27 in 2008 [source: EUROSTAT, 2011]

Cooling appliances like refrigerators and freezers have a substantial share in the residential electricity use. According to the International Energy Agency cooling appliances consumed 13.4 % of total energy in the residential sector in 2000. This corresponds to 314.6 TWh [IEA, 2003]. Referring to large domestic appliances, refrigerators have the highest share of total appliances electricity use (cf. Figure 2-2) [ADEME, 2009]. Therefore, the energy consumption of household cooling appliances has attracted considerable attention in recent decades. As a consequence, several governments worldwide intervened by implementing energy efficiency standards and labels in order to remove inefficient products from the market. [TURIEL, 1997, SAIDUR et al., 2002]

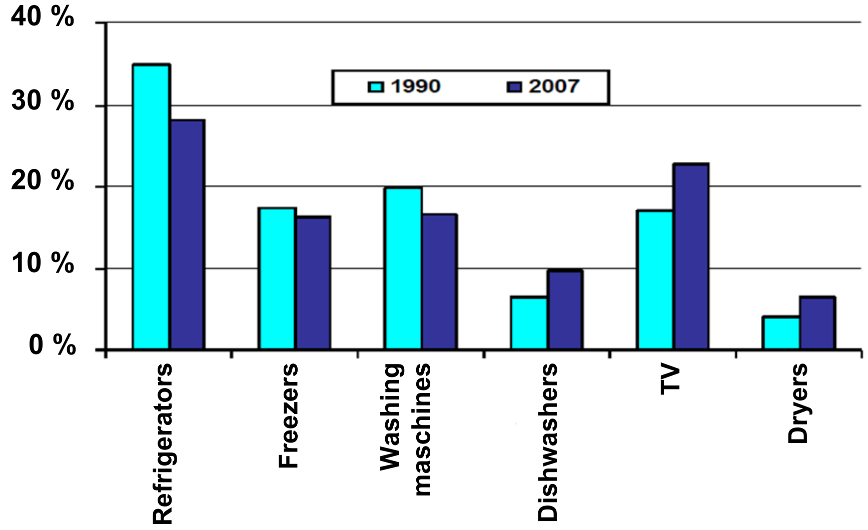

Figure 2-2: Share of large household appliances in total appliance electricity use [ADEME, 2009]

2.2 Design and functional principle of refrigerators

Nowadays, refrigerators are almost common in every household in developed countries. Worldwide, there are about 1 billion domestic refrigerators and freezers [BILLIARD, 2002]. According to ZVEI [2011], the market saturation in Germany summed up to 100 % for refrigerators and 54 % for freezers in 2010. With an average saturation of 106 % the European market for refrigerators and fridge-freezers is already oversaturated meaning some households have more than one appliance. Freezers show penetration rates of about 52 % for EU-15 [STAMMINGER, 2001].

Refrigerators are used to store perishable food and to protect food from bacterial growth. For this purpose, heat from the low temperature region inside the cooling compartment has to be removed. This heat enters the compartment by warm food or by conduction and convection through the wall. [WHITMAN et al., 2005, KURZHALS, 2007]

According to the second law of thermodynamics, heat flows in the direction of decreasing temperatures. That means that the heat transfer from a low temperature to a high temperature region cannot occur by itself. It requires some kind of heat pump and additional energy input. [CENGEL, 2007]

Refrigerators intended for household use are cyclic devices that normally operate using the vapour-compression system [PICHERT, 2001]. The operation principle of an actual refrigeration cycle is akin to the principle of a reversed Carnot cycle [BERGMANN and SCHAEFER, 1974].

2.2.1 The reversed Carnot cycle

The reversed Carnot cycle is the most efficient thermodynamic cycle possible for creating a temperature difference by doing a given amount of work. It is an idealised hypothetical cycle using perfect gases as a working fluid and consists of four reversible processes in succession (cf. Figure 2-3 and Figure 2-4):

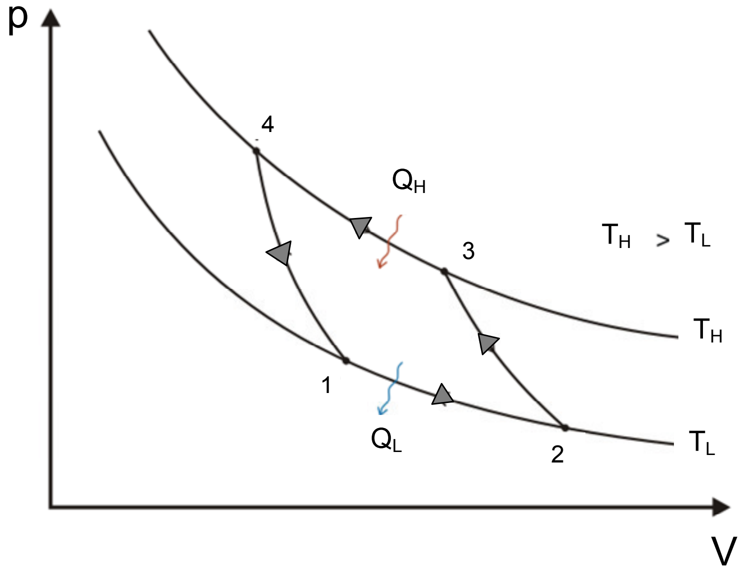

Figure 2-3: Reversed Carnot cycle illustrated on a pressure volume diagram [own illustration based on BERGMANN and SCHÄFER, 1974]

During the process 1-2 (isothermal expansion), a heat amount Q_L is absorbed isothermally by the working fluid at a low temperature T_L. Following, the working fluid is compressed isentropically with the aid of external work (process 2-3). At the same time, the temperature of the fluid rises from T_L to T_H. Process 3-4 describes the isothermal compression of the working fluid. During this process, heat in the amount of Q_L is rejected isothermally to a high-temperature sink at the temperature T_H. Finally, the working fluid expands isentropically accompanied by a declination of the temperature from T_H to T_L (process 4-1). [CENGEL AND BOLES, 2007]

According to LÜDECKE and LÜDECKE [2000], the coefficient of performance (COP) of a Carnot refrigerator (CR) can be expressed as

$$COP_{CR} = \frac{Heat_{absorbed}}{Work_{input}} = \frac{Heat_{absorbed}}{Heat_{rejected} - Heat_{absorbed}} = \frac{T_L}{T_H - T_L} \tag{2-1}$$

COP_{CR} = coefficient of performance of a Carnot refrigerator, T_L = temperature of the lower isotherm, T_H = temperature of the higher isotherm

The Carnot cycle cannot be approached in an actual cycle. Indeed, the two isothermal processes (1-2 and 3-4) can be approximated in practice. However, it is not possible to approach the processes 2-3 and 4-1 of a reserved Carnot cycle in actual devices. The execution of process 2-3 requires a compressor that is able to handle a liquid-vapour-mixture. The process 4-1 also involves the expansion of two-phase working fluid in turbine. [CENGEL, 2007]

As a consequence, the reversed Carnot cycle is not a suitable model for refrigeration cycles in practice. However, it provides the upper limit of what is possible in actual devices and therefore it serves as a standard against which actual cycles can be compared. [BAHRAMI, 2011b]

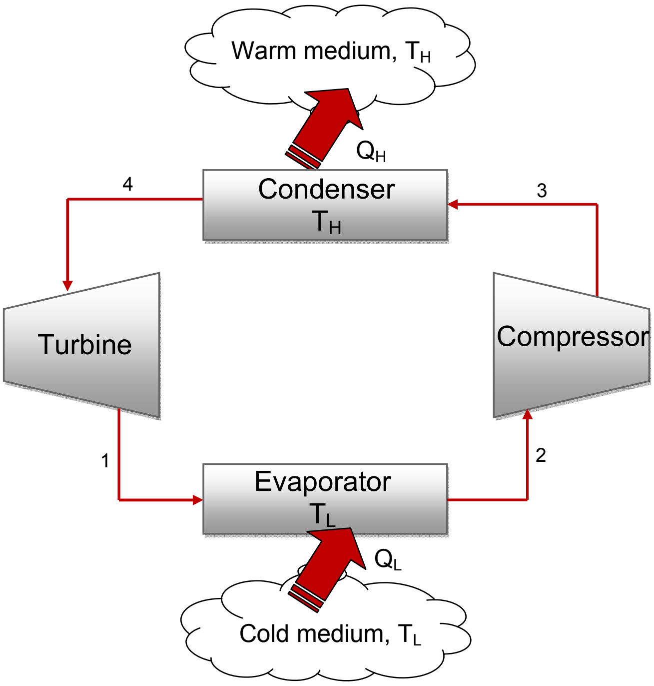

Figure 2-4: Scheme of a Carnot refrigerator (own illustration modified from ÇENGEL, 2007)

2.2.2 The vapour-compression refrigeration cycle

The vapour-compression refrigeration cycle is the most widely used refrigeration cycle in practice. Its principle is also applied to every common domestic refrigerator. The objective of this cycle is to transfer heat from a low-temperature region (inside the refrigerator) to a high-temperature one (outside the compartment). The heat transfer is enabled by a refrigerant that changes its state of aggregation.

Analogous to the Carnot cycle, it consists of an evaporator, a compressor and a condenser. However, the turbine is exchanged by an expansion (or throttle) valve in the vapour-compression refrigeration cycle (cf. Figure 2-5) and consequently this cycle is not reversible.

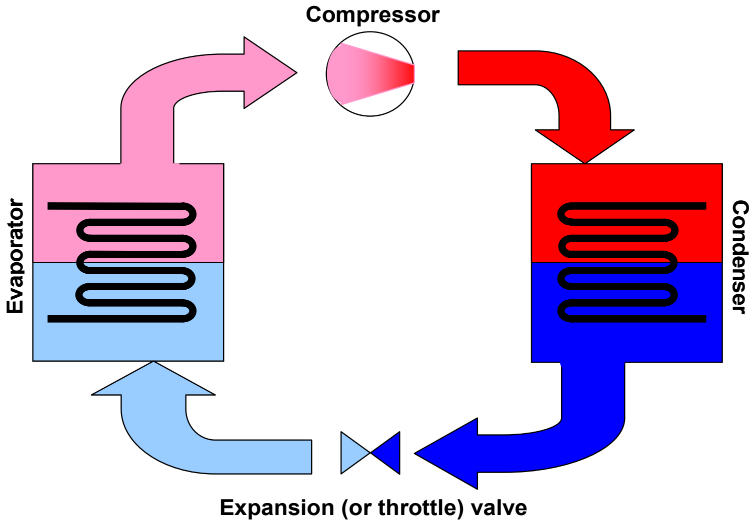

Figure 2-5: Principle and components of a vapour-compression refrigeration set (own illustration)

In terms of the vapour-compression refrigeration cycle a distinction is made between the ideal and the actual vapour-compression cycle.

In compliance with the reversed Carnot cycle, the ideal cycle is composed of four different processes in succession. During process 1, a working fluid (a two-phase mixture), also called refrigerant, is evaporated to a saturated vapour. The necessary heat is supplied by the refrigerated space that surrounds the evaporator. Subsequently, the saturated vapour is compressed adiabatically to a superheated vapour, that means a vapour whose temperature is higher than the boiling point temperature of the corresponding pressure [THE ENGINEERING TOOLBOX, 2011b]. During process 3, the refrigerant rejects most of its energy. In doing so, it is de-superheated and condensed to a saturated liquid. Finally, the temperature and pressure of the working substance decrease through a throttling process and the cycle is completed by re-entering the evaporator. [WHITMAN et al., 2005]

For this ideal vapour-compression cycle, several assumptions have to be made. It is assumed that there are no frictional pressure drops and that the refrigerant flows at constant pressure through the evaporator and the condenser. Furthermore, irreversibility within evaporator, compressor and condenser as well as stray heat losses to the surroundings are ignored. Additionally, the compression process is assumed to be isentropic. [BAHRAMI, 2011a]

On some points the actual vapour-compression cycle deviates from the ideal one as a result of irreversibility in different components and heat losses to the surroundings. The key difference between both cycles, however, is that the compression process is not isentropic in practice. As a consequence, more energy has to be spent at the compressor in order to obtain the same final pressure in practice. Moreover, the refrigerant enters the compressor as a superheated vapour instead of a saturated one like in ideal cycles. This is to avoid harmful liquid droplets within the compressor. In addition, the liquid refrigerant is slightly subcooled in actual cycle before it enters the throttling valve. This process ensures that the refrigerant is completely condensed at the inlet of the throttle valve and it increases the heat that can be absorbed from the refrigerated space. [BAHRAMI, 2011a, CENGEL, 2007]

In refrigerators the refrigerant circulates inside a closed loop piping system. Refrigerants are characterized by low boiling temperatures, a high heat of vaporization and a high critical temperature. [PICHERT, 2001] In the field of domestic refrigerators chlorofluorocarbons (CFC's) were used as refrigerants over a long period. Because of their high ozone depletion potential (ODP) and high global warming potential (GWP) the chlorinated compounds were banned from the supply and use and they were replaced by HFC's or FC's like Tetrafluoroethane (R-134a) and certain blends. Nowadays, different saturated hydrocarbons like Isobutane (R-600a) are widely used as refrigerants in domestic refrigerators [HEA, 2010]. The boiling point of these refrigerants is about – 26.3 °C (R-134a) and – 11.7 °C (R-600a) [THE ENGINEERING TOOLBOX, 2011a].

As mentioned above, the purpose of vapour-compression refrigeration cycle is to remove heat from inside the refrigerator that enters the compartment by conduction through the cabinet wall, by convection or by warm food [WHITMAN et al., 2005]. The heat flow q (in $W \cdot m^{-2}$) through solids can be described by a basic equation:

$$\frac{\Delta Q}{\Delta t} = -\lambda \cdot A \frac{\Delta T}{\Delta \delta} \tag{2-2}$$

$\frac{\Delta Q}{\Delta t}$ = amount of heat transferred per unit time in W, A = cross-sectional surface area in m^2, λ = thermal conductivity, a material constant in $W \cdot K^{-1} \cdot m^{-1}$, ΔT = temperature difference between the two ends of the solid in K, $\Delta\delta$ = distance between the two ends of the solid in m

The equation 2-2 is called Fourier’s law of conductivity. According to this, the amount of heat transferred per unit time is directly proportional to the temperature gradient and the surface area and inversely proportional to the thickness of the solid [LABUHN and ROMBERG, 2009].

2.3 Domestic refrigerators’ energy efficiency standards and labels

Due to the considerable share of refrigerators and freezers on residential energy consumption, there are several countries worldwide that implemented any programmes to regulate this issue. In most cases, the programmes were introduced in form of minimum energy efficiency standards (MEPS) or comparative labels [HARRINGTON, 2009, MAHLIA et al., 2004]. WIEL and MCMAHON [2005] defined energy-efficiency standards as ‘procedures and regulations that prescribe the energy performance of manufactured products, sometimes prohibiting the sale of products that are less efficient than a minimum level’. So called minimum energy efficiency standards (MEPS) were enacted, amongst others, in Australia, Canada, Europe, US and in parts of Asia and Latin America [MAHLIA et al., 2003], mostly in a mandatory form [MAHLIA et al., 2004].

Energy efficiency labels are stickers affixed to products or products’ packaging that describe their energy efficiency. They often serve as a complement to energy efficiency standards and provide necessary information for consumers to make a well informed purchase decision. Furthermore they provide a benchmark for utility companies and governmental energy conservation agencies to offer incentives for consumers to buy the most efficient products. [SAIDUR et al., 2005, MAHLIA et al., 2002]

Four types of labels have to be distinguished [SAIDUR et al., 2005, DAVIS et al., 1998]:

- Seals of approval (endorsement labels, given according to pre-specified criteria, e.g. blue angle in Germany)
- Single-attribute certification programs (only address one attribute of a product, e.g. energy star label of the U.S. Environmental Protection Agency)
- Information disclosure (summarise product data, but do not provide a simple system to compare different products, e.g. US energy guide program)
- Comparative label (provide a system to compare performance among all available models, e.g. European Energy Label; it uses either a discrete ranking system or a continuous scale)

The way of presentation of information is thought to be the main factor influencing the effectiveness of a label [WIEL and MCMAHON, 2005].

The US label for refrigerators is a consumption label. In addition to the yearly energy consumption in kWh, it shows the cost per year in \$. It does not contain any efficiency indicator, but features the lowest and highest energy use of similar models. [HARRINGTON, 1997]

The Australian label shows, besides an estimation of yearly energy consumption, an energy efficiency rating presented in the form of 1 to 6 stars. The more stars are shown on the label, the higher the efficiency of the respective appliance. [BROWN, 1998]

The EU label also features the energy consumption per year measured according to the standard. Furthermore, an efficiency indicator is given in form of a seven-step scale. [BROWN, 1998]

The foundation of all energy efficiency standards and energy efficiency label are energy test procedures, that means agreed-upon methods of measuring energy performance of appliances [WIEL and MCMAHON, 2005]. Their objective is to provide a way for manufacturers, regulatory authorities and for consumers to compare and evaluate consistently the energy performance of different appliances [MEIER and HILL, 1997, MAHLIA and SAIDUR, 2010].

According to MEIER and HILL [1997] and WIEL and MCMAHON [2005], the ideal test procedure meets the following criteria:

- Repeatability and accuracy of results
- Inexpensive to perform
- Accurate prediction of energy use under actual conditions
- Easy comparison of results with the results of other test procedures
- Reflection of the relative performance of different design options for a given appliance

However, the aforementioned goals usually conflict with each other. A test procedure for example that reliably reflects actual conditions is expensive and complicated to perform. As a result, a test procedure always is a compromise. [WIEL and MCMAHON, 2005]

2.3.1 Test procedures

Worldwide, there are several established test procedures for domestic refrigerators. Each procedure is developed to coincide with the local conditions of the particular country or region. The three most important of them are the Department of Energy (DOE), partly using the ANSI/AHAM HRF-1-1988 (AHAM), the Japanese Industrial Standards (JIS) and the International Standard Organization (ISO). [MEIER, 1995] Table 2-1 provides a comparison between the energy consumption test methods.

Department of Energy Test (DOE; ANSI/AHAM)

The current American National Standard containing the energy consumption test for refrigerators is ANSI/AHAM HRF-1-2008. However, energy consumption data in U.S.A. are mostly determined under the U.S. Department of Energy Code of Federal Regulations (C.F.R. Part 430 Subpart B Appendices A1 and B1) and DOE regulations have precedence with regard to all mandatory U.S. Government requirements for energy labeling and minimum efficiency performance standards. DOE test refers in

parts to AHAM Standard, and other parts are modified again. [WWW.ENERGYRATING.GOV.AU, 2009]
For all tests the ambient temperature is 32.3 °C (90 °F). Ambient humidity is not specified for energy consumption tests. A fresh food compartment temperature of 3.3 °C (38 °F) is specified for all refrigerators except refrigerator-freezers. In the case of the latter, the fresh food compartment temperature has to be below 7.22 °C (45 °F). With regard to the freezer temperature, DOE and AHAM distinguishes between refrigerator-freezers and separate freezers. Temperatures that have to be applied are -15 °C and -17.8 °C (5 °F and 0 °F), respectively. During the testing procedure, all doors are kept closed. According to DOE test procedure, no load is specified for freezer compartment of automatic defrost refrigerator-freezers and all refrigerators with ice-makers. Likewise, the fresh food compartment remains unloaded. [WWW.ENERGYRATING.GOV.AU, 2009]

Japanese Industrial Standard (JIS)

JIS C 9801 is the relevant standard for testing energy consumption of household refrigerating appliances in Japan. According to TSURUSAKI et al. [2010] and BANSE [2000], the JIS standard was made in 1979 and several times revised for the purpose of harmonization with ISO standard. The present test procedure includes door openings of both fresh food and freezer compartment and specifies ambient humidity. Additionally, load has to be placed in fresh food (500 ml of water in bottles for each 75 l of volume) and freezer compartment (125g of ISO test packages for each 20 l of freezer volume) during test process. At the time of placement, load should be at ambient temperature. Energy consumption is measured at two different ambient temperatures (15 °C and 30 °C) each for a test period of 24 h. The annual energy consumption is calculated by weighting the two results assuming 180 days at 30 °C and 185 days at 15 °C. [TSURUSAKI et al., 2006, HARRINGTON, 2009]

International Standard Organisation (ISO)

Due to little input from outside Europe the ISO standard is largely orientated towards European conditions and appliances [MEIER, 1995, HARRINGTON, 2009]. ISO standard specifies 25 °C as the ambient temperature for energy consumption tests of all climatic classes except the tropical class. The latter is tested at 32 °C. Relative ambient humidity inside the test chamber should be kept within the range 45 and 75 %. The test period is at least 24 h comprising a whole number of operating cycles[1]. The freezer compartment is required to be loaded during energy consumption test. The load material consists of ISO test packages that mimic the thermal characteristics of lean beef. Test packages have to be stacked until the freezer compartment is essentially full except a minimum required space between the stacks. All doors are kept closed during the test period. [ISO, 2005, Yashar, 2003]

Table 2-1: Requirements of selected energy consumption test procedures (own illustration based on Tsurusaki et al. [2006], Meier [1995], Mahlia and Saidur [2010], Harrington [2009], Harrington [2000]

Parameter		**ANSI/AHAM HRF-1**	**JIS C 9801**	**ISO 15502** **IEC 62552[2]**
Ambient temperature		32.3 ± 0.6 °C	30 °C: 180 days 15 °C: 185 days	25 ± 0.5 °C/ 32 ± 0.5 °C
Ambient humidity		not specified	30 °C: 75 ± 0,5 % 15 °C: 55 ± 0,5 %	45-75 %
Compartment temperature	fresh food	3.3 °C/ 7.22 °C	≤ 4 °C	5 °C
	freezer	-15 °C/ -17.8 °C	≤ -18 °C	-18 °C
Door openings	fresh food	no	35 times	no
	freezer	no	8 times	no
Load	fresh food	none	placement of load during testing process	none
	freezer	none		load with thermal characteristics of lean beef

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[1] An operating cycle is the period commencing at the initiation of an automatic defrosting cycle and terminating at the moment of initiation of the next automatic defrosting cycle (frost-free-systems) or the period between two successive stops of the refrigerating system

[2] The Internal Electrotechnical Commission (IEC) is a worldwide organization for standardization that comprises all national electrotechnical committees. The International Standard IEC 62552 cancels and replaces International Standard ISO 15502.

The relevant European measurement standard is EN 153:2006, referring to EN 15502:2005. The latter is the European implementation of the former worldwide standard (ISO 15502). The EN 153 and ISO test procedures are most widely identical with the exception of ambient temperatures. ISO standard specifies two different ambient temperatures for energy consumption test. Energy consumption is measured at an ambient temperature of 25 °C for all climatic classes[3] (Sub Normal (SN): +10 °C to +32 °C; Normal (N): +16 °C to +32 °C; Sub Tropical (ST): +16 °C to 38 °C) except the Tropical class T (16 °C to 43 °C). The latter is tested at an ambient temperature of 32°C. According to the EN 153:2006 standard, all appliances, regardless of their climatic class, are tested at a temperature of 25 °C. [EUP PREPARATORY STUDIES LOT 13, 2008]

Due to high differences in test conditions, the energy consumption of the same appliances can considerably differ from one standard to another. Studies by BANSAL [2001] revealed that the performance of an appliance is best when tested according to the standard it is designed for. However, refrigerators are products with a large international trade and as such, they have to meet all mandatory requirements of the markets they are sold. Because refrigerators are complicated thermodynamic products, it is not easy to convert energy consumption between different standards. As a consequence, appliances have to be tested several times according to all standards of the markets, in which they are offered for sale. That results in high expenditure of time and costs for exporters. [HARRINGTON, 2009]

For this reason, there are several approaches to make the testing process easier and fairer. A study by BANSAL and KRUGER [1995] aimed to develop an algorithm that enables the conversion of energy consumption from one standard to another. The investigation concentrates on the Australian-New Zealand Standard (ANZS), the International Standard (ISO), the American National Standard (ANSI), the Japanese International Standard (JIS), and the Chinese National Standard (CNS). The proposed formula reflects the experimental results quite well with exception of Japanese

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[3] The climatic classes define the ambient temperature range under which the appliance should be operated.

standard. A further approach by HARRINGTON [2009] is the development of a new global test standard for refrigerators that represents actual use in different parts of the world.

2.3.2 Test standard versus actual energy consumption

Several authors highlighted the positive impact of energy labelling on energy efficiency [WAIDE, 2001, HARRINGTON and WILKENFELD, 1997]. Caused by the implementation of the Energy Label in combination with MEPS, the share of class A and B appliances in the European market for example increased from 10 % in 1990-1992 to roughly 57 % in 1999 [WAIDE, 2001]. This trend also continued in the years that followed. Because of a high market share of class A appliances, the European label for household refrigerators and freezers was amended by the introduction of two additional efficiency classes A+ and A++ [EUROPEAN COMMISSION, 2003]. Ongoing efficiency improvements led to a further alignment of the European label in 2010 [EUROPEAN UNION, 2010, CECED, 2011].

In spite of this benefit, energy labels and especially the European one, which is based on ISO standard, are time and again criticized by consumer bodies and experts [MTP, 2006]. The main criticism centres on the fact that the test conditions are artificial and so the test does not represent realistic usage. Nevertheless, the energy consumption test is performed at an ambient temperature of 25 °C, which is higher than the average ambient temperature in private homes. This increased temperature is assumed to compensate for the lack of door openings. [MTP, 2006] However, investigations dealing with the comparison of actual energy consumption of domestic refrigerators in field and labelled values are sparse and often limited to one special region.

A study by SIDLER et al. [2000] metered appliances in 98 households in south central France for a period of one month. They concluded that declared values on the Energy Label reflect average annual energy consumption of appliances in the respective region. However, there were high individual variations in energy use. Because of that, there was no strong correlation between labelled and measured values on an individual level.

Investigations of the Istituto Italiano del Marchio di Qualità (IMQ) revealed that the European standard overestimates actual consumption by 10-12 % assuming a yearly average kitchen temperature of 18-19 °C [MORETTI, 2003].

The Market Transformation Programme [MTP, 2006] compared the energy consumption of twelve cooling appliances under European standard test conditions and more realistic conditions (ambient temperature of 20 °C, a series of door openings). The study concluded that energy consumption under both conditions are either identical or labelled values are a bit higher than actual values.

For DOE standard, SPOLEK [1985] compared labelled energy consumption values with home-use values based on a literature review. The study revealed that actual energy consumption is on average 5 % higher than predicted according to standard. Nevertheless, DOE standard was assumed to be an excellent predictor of energy consumption under real life conditions.

Further comparisons were performed by MEIER and JANSKY [1991]. They found that the field use of investigated refrigerators were on average 15 % lower than labelled values with high individual variations. However, these variations offset each other and the study concluded that DOE standard and the associated label are a moderately good predictor of energy consumption in the field.

2.4 Consumers' handling and practices in home refrigeration

Consumer behaviour in handling refrigerators does not only influence the shelf life and quality of the food stored inside but also the refrigerator's energy consumption [GEPPERT and STAMMINGER, 2010, EUP PREPARATORY STUDIES LOT 13, 2008]. A variety of processes along the whole food chain from retail store to the retrieval of the food from the refrigerator are involved. Several studies dealt with the investigation of behaviour pattern in using domestic refrigerators and handling chilled foods.

2.4.1 Food shopping habits

Shopping habits as well as transport from retail store to the domestic refrigerator have a considerable impact on food safety and quality [THOMAS, 2007]. Besides that, they also influence the thermal load of a refrigerator caused by the storage of food. The thermal load depends, amongst others, on the temperature at which the food is loaded into the domestic refrigerator. The higher the food temperature the higher is the thermal load and along with this the energy consumption. After removal from chilled display, unprotected chilled food warms up while shopping and transportation [EVANS, 1998]. The increase in temperature depends on both, time and ambient temperature.

Chilled foodstuff is bought at least one time per week whereas most people surveyed in a UK study shopped for food 3 or 4 times per week (33.7 %) and 5 to 7 times per week (26.2 %), respectively [EVANS, 1998]. According to COLWILL [1990], consumers spend an average of 42 minutes in grocery store making a bulk purchase. Chilled products were removed from refrigerated counter within 15 minutes of arrive at the store.

The time lapse from retail store to the domestic refrigerator was investigated in several studies. A mean transportation time of 43 minutes was stated by JAMES and JAMES [2002]. Shorter transport times of 36 and 25 minutes, respectively, were found by EVANS [1992] and JEVSNIK et al. [2008]. JAY et al. [1999] as well as KENNEDY et al. [2005a] reported that more than 50 % of surveyed persons took less than 30 minutes to get their food home. GILBERT et al. [2007b], WORSFOLD and GRIFFITH [1997] and SPRIEGEL [1991] found even up to 90 % of consumers taking less than 30 minutes to complete their journey from retail store to the home. However, there were also a number of respondents indicating a time lapse up to 90 minutes or even 2 hours [THOMAS, 2007, EVANS, 1992, KENNEDY et al., 2005b, JAY et al., 1999].

Transport air temperatures between 7.5 °C in February and 32 °C in July were recorded in a UK study by WORSFOLD and GRIFFITH [1997]. Inspite of these high temperatures, only 29 % of respondents in this study used an isolated bag or a cool box to transport perishable food in summer. According to JEVSNIK et al. [2008] and EVANS

[1992], the percentage of users of a cool bag or box is even smaller (15.3 % and 12.7 %).

The increase of product temperature during one-hour transportation was investigated by EVANS [1998]. A total of 19 different chilled products were monitored in this study. One sample of each product was stored in a pre-cooled insulated box filled with ice packs. The other sample was placed in the boot of the car. The external ambient temperature was within the range 23 to 27 °C during the tests. Whereas the temperature of the foodstuff stored in the insulated bag remained constant or even slightly decreased, the temperature of the products placed in the boot partially rose up to almost 40 °C. Especially thinly sliced products were affected by a high rise in temperature. After storing in the domestic refrigerator, the foodstuffs required several hours to reach the compartment temperature. That implicates a negative impact on both, food safety and energy consumption of the refrigerator. This impact may further be intensified by placing hot or warm food into the refrigerator. LAGENDIJK et al. [2008] found 28 % of consumer storing hot or warm food seldom in the refrigerator and 2 % doing so often.

Besides the product temperature, the thermal load caused by the storage of food also depends on the quantity of stored food. However, no study was found that examined the quantity of food, which was stored in the refrigerator per day or after a purchase.

2.4.2 Internal refrigerator temperatures

One of the most investigated parameters in home refrigeration is the internal temperature of domestic cooling appliances (Table 2-2). The results of European surveys are very similar with operating temperatures ranging from 0 to 12 °C. Most studies stated an overall mean temperature of about 6 °C and maximum temperatures varying within the range 11.4 to 14.5 °C. Similar findings were also obtained in surveys outside Europe. An investigation carried out in New Zealand found 60 % of refrigerators operating at temperatures above 4 °C [O'BRIEN, 1997]. The mean temperature in this study was 4.9 °C. A further New Zealand study by GILBERT et al.

[2007a] revealed similar data. Temperatures were measured by placing data logger on the front of the top and bottom shelves of 127 refrigerators. 55 % of appliances were reported to operate above 5 °C and 34 % above 6 °C. A US study [KOSA et al., 2007] with 2060 participants found 28 % of refrigerators surveyed operating above the recommended temperature of 4.4 °C. The provided data, however, may not be strictly comparable because of different kind of sensors and positions of measurement. Additionally, the results may vary depending on the season. JAMES and EVANS [1992a] for example found one third of survey participants lowering the internal temperature adjustment in summer.

Table 2-2: Internal refrigerator temperatures – a comparison of results from surveys and direct observations

Reference	**Country**	**Number of samples**	**Measurement**	**T_{min}**	**T_{mean}**	**T_{max}**	**% T > θ °C**
James and Evans [1992a]	UK	252	Data logger on top, middle, bottom shelf	- 0.9 °C	6 °C	11.4 °C	33.3 % ≥ 7 °C 7.3 % ≥ 9 °C
Kennedy et al. [2005b]	Ireland	100	Data logger on middle shelf	- 1.7 °C		11.8 °C	71 % > 5 °C
Terpstra et al. [2005]	The Netherlands	31	Thermometer in water bottle inside the door	3.8 °C		11.5 °C	68 % > 7 °C
Sergelidis et al. [1997]	Greece	136	Electronic thermometer				55.1 % ≥ 9 °C 25 % > 10 °C
Hudson and Hartwell [2002]	UK	16	Temperature probe				81 % > 5 °C
Laguerre et al. [2002]	France	119	Data logger on top, middle, bottom shelf	0.9 °C	6.6 °C	11.4 °C	80 % > 5 °C
Marklinder et al. [2004]	Sweden	102	Product temperatures				
Worsfold and Griffith [1997]	UK	108	Data logger strapped on perishable food	2 °C	5.9 °C	12 °C	58 % > 5 °C
Flynn et al. [1992]	North Ireland	150	Thermometer on top, middle, bottom shelf	0.8 °C	6.5 °C	12.6 °C	71 % > 5 °C
Azevedo et al. [2005]	Portugal	86	Digital Thermometer				70 % > 6 °C 12 % > 10 °C
Garrido et al. [2010]	Spain	33	Temperature probes	0.6 °C		14.5 °C	

2.4.3 Door openings

Also the frequency and duration of daily door openings are manyfold investigated factors. Partially, the results of the studies are based on estimations made by the participants, and yet others are based on measurements. Table 2-3 provides an overview of the published results concerning the frequency of daily door openings.

All studies found high variations in refrigerator use. The number of daily door openings ranges from one time up to 240 times per day. Such high frequencies, however, were the exception rather than the rule. The vast majority of households opened the door of their refrigerator less than 30 times per day.

According to Evans [1998], the doors remained open averagely for 7.3 seconds. That summed up to a total of 3.1 minutes per day (range 0.2 to 11.5 minutes). Thomas [2007] found an average door opening time of 15 seconds. The total door opening time per day recorded in her study was within the range 1.5 to 19.3 minutes.

Table 2-3: Overview of published results regarding frequency of daily door openings

Reference	**Region**	**Number of samples**	**Results based on**	**Frequency** min	**Frequency** mean	**Frequency** max	**% < x time/d**
Derens et al. [2001]	France	119	Guesses				19 % < 10 43 %: 10-20 38 % > 20
Thomas [2007]	Europe	34	Measure-ment	4	24.7	67	
Saidur et al. [2008]	Malaysia	104	Guesses				17 % < 10 39 %: 10-20 28 %: 21-30 11 %: 31-40 5 %: > 40
Evans [1998]		60	Measure-ment	1	39	240	60 % < 30

2.4.4 Ambient/ room temperature

Although the ambient temperature is said to have a crucial influence on refrigerators energy consumption, there appears to be little published data on the actual ambient conditions in private homes apart from four studies carried out in Europe [JAMES and EVANS, 1992a, HUNT and GIDMAN, 1982, THOMAS, 2007, EUP PREPARATORY STUDIES LOT 13, 2008].

The study by JAMES and EVANS [1992a] was conducted on a sample of 252 household in UK. They found a mean kitchen temperature of 20.6 °C. 72.2 % of kitchens were of a temperature between 17 and 23 °C.

HUNT and GIDMAN [1982] carried out a survey in UK during the heating season (February and March). They recorded temperatures of each room in 881 homes nationwide different. The study showed that the mean kitchen temperature was 16.7 °C with a standard deviation of 3.1 °C.

In the study carried out by THOMAS [2007] a data logger was integrated into the control panel of 40 refrigerators in four European countries. Over a period of 1.5 years, a total of 10 observation periods took place, one every 2 month. During each observation period, the ambient temperature, among other things, was recorded every minute for 36 consecutive days. The temperatures recorded in each period and in each individual household were analysed. The lowest of all recorded ambient temperatures was – 1.1 °C and the highest 37.5 °C with an overall mean of 24.2 °C. Most of all temperatures (86.2 %) were within the range 20 to 30 °C. 0.4 % of recorded values were lower than 10 °C and 6.5 % higher than 30 °C.

In the EUP PREPARATORY STUDIES [2008], a total of 2497 households in 10 European countries were asked to estimate the minimum and maximum ambient temperature in the room, where the refrigerator is located. Minimum temperature values ranged from 0-3 °C to 20-23 °C with an average of 14.6 °C. Whereas more than 50 % of the Scandinavian, the Eastern European, the French and the German households presented minimum temperatures higher than 16 °C, especially the South European participants in Italia and Spain showed predominately very low values. In terms of maximum temperatures, it is almost the other way round. More than a quarter of Southern

European respondents stated that they reach very high ambient temperatures of at least 28 °C. The majority of the consumers from the other countries answered that the maximum ambient temperature lies in a moderate range between 20 and 27 °C. The overall average maximum temperature is 24.4 °C. All in all, the estimated maximum temperature values were within the range 12 °C to over 44 °C.

The different places, where the refrigerators are located in private homes, can be regarded as a reason for these high variations in ambient temperature. Most of appliances seem to be placed in a heated room, e.g. the kitchen, where the temperature is relatively constant over the year. Other refrigerators, however, are located in an unheated room like a cellar, a garage or a balcony, where they are exposed pretty much to the seasonal changes in temperature [EUP PREPARATORY STUDIES LOT 13, 2008].

2.4.5 Filling level

There appears to be little published data on the rate of utilization of refrigerators' net volume although several populist sources recommend keeping the refrigerator as full as possible to reduce the energy consumption.

SAIDUR et al. [2008] carried out a survey in Malaysia using a questionnaire. A sample of 104 participants had to estimate whether their refrigerator is empty, half loaded or fully loaded. Most of respondents assessed their refrigerator as fully loaded (39.42 %) or half loaded (53.85 %). 6.73 % of participants stated that their appliances are empty. More detailed investigations concerning refrigerators' filling level were not found.

2.5 Impact of consumer behaviour on refrigerators' energy consumption

Several studies and institutions have already examined how consumer handling of refrigerators influences their energy consumption and how this energy consumption can be reduced.

The following factors which allegedly may have an impact on energy consumption were mainly investigated in previous studies:

- room/ambient temperature
- compartment temperature of the refrigerator
- door openings
- additional heat load by warm food placed in the refrigerator
- filling level

2.5.1 Room/ ambient temperature

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers ASHRAE [1988], 60-70 % of refrigerators heat load is caused by conduction through cabinet walls. This conduction is determined by the temperature difference between the ambient and the compartment temperature. Consequently, it is clear from basic physics and also reported in several studies that energy consumption of refrigerators is closely related with the ambient temperature [GEPPERT and STAMMINGER, 2009, BENNICH et al., 2009]. Furthermore, the ambient temperature also influences the compressors efficiency whereas the efficiency decreases with rising ambient temperatures. [SAIDUR et al., 2002]

There is extensive literature concerning the impact of changes in ambient temperature on the energy consumption. A study by LEPTHIEN [2000] showed that 18-19 % of energy can be saved when the room temperature is 20 °C instead of 25 °C. Similar findings were also obtained by VAN HOLSTEIJN EN KEMNA BV [VHK, 2005], THE HESSIAN MINISTRY OF ECONOMY, TRANSPORT, URBAN AND REGIONAL DEVELOPMENT [HMWVL, 2005], WICKE and BÖHMER [1998], SAIDUR et al. [2000] and further authors (cf. Table 2-4).

Table 2-4: Impact of ambient temperature on refrigerators’ energy consumption

Reference	Ambient/ room temperature variation	Impact on energy consumption
LEPTHIEN [2000]	Reduction from 25 to 20 °C	- 18 to 19 %
VHK [2005]	Reduction from 25 to 20 °C	- 15 to 20 %
HMWVL [2005]	Reduction from 25 to 21-23 °C	- 16 %
WICKE and BÖHMER [1998]	Reduction from 25 to 24 °C	- 8 %
SAIDUR et al. [2000]	Temperature variation within the range 16 °C to 31 °C	+ 40 Wh/day per 1 °C increase in temperature
TSURUSAKI et al. [2006]	Reduction from 25 to 22 °C	-13 %
PROCTOR [1993]	Rise from 65 °F to 80 °F	+ 100 %
KAO and KELLY [1996]	Rise from 21.1 °C to 32.2 °C	+ 91 Wh/day per °C (top-mounted freezer) + 120 Wh/day per °C (Side-by-side-door)
HASANUZZAMAN et al. [2009]	Temperature variation within the range 18 °C to 30 °C	+ 42 Wh/day per 1 °C increase in temperature
BANSAL [2000]	Rise from 10 °C to 25 °C Rise from 25 °C to 32 °C Rise from 10 °C to 32 °C	+ 40 % + 20 % + 50 %

2.5.2 Compartment temperature

Besides the ambient temperature, the refrigerators’ energy consumption is also quite sensitive to the temperature setting inside the compartment. Both factors act in an inversely proportional manner. If the thermostat is reset to a lower temperature, the energy consumption rises and vice versa. [LEPTHIEN, 2000]

Several previous studies aimed to quantify the effect of the compartment temperature setting on refrigerators’ energy consumption and the results are extensively consistent. MEIER [1994] found an average 18 % increase in energy use by lowering freezer temperature by 5 °F. That means a 6.5 % increase for each degree centigrade reduction. SAIDUR et al. [2002] estimated that freezers’ energy consumption rises by about 7.8 % per degree centigrade temperature reduction. The following Table 2-5 summarises the results of previous studies.

Table 2-5: Impact of internal temperature setting on refrigerators' energy consumption

Reference	Compartment temperature variation	Impact on energy consumption per °C
MEIER [1994]	Reduction of freezer temperature by 5 °F	+ 6.5 %
SAIDUR et al. [2002]	Variation of freezer thermostat setting position within the range 1 to 10	+ 7.8 %
WICKE and BÖHMER [1998]	Increase of refrigerator temperature from 5 to 7 °C	- 6.5 %
LEPTHIEN [2000]	Increase of refrigerator temperature from 4.9 to 7.5 °C (5.1 to 6.9 °C)	- 10.9 % (-14.3 %)
SIDLER et al. [2000]	Reduction of freezer temperature from -18 to -21.1 °C	+ 5.7 %

Besides the energy consumption, refrigerators' compartment temperature is also associated with food safety and quality in several studies. There is extensive literature concerning shortened shelf life of perishable food caused by high storage temperatures and extension of shelf life caused by reduction of storage temperature. KREYENSCHMIDT [2003] reported that shelf life of poultry meat is about 2-3 days when stored at 10 °C whereas storage at 4 °C results in a shelf life of roughly 5-6 days. Similar findings were also obtained by BEM and HECHELMANN [1994]. A general rule of thumb is that bacterial growth rate doubles with every 10 °C rise in temperature [GILL, 1986]. According to JAMES and JAMES [2002], this phenomenon is even more pronounced in low temperature range. Below 10 °C, cold-storage life is halved for 2-3 °C rise in temperature. A storage temperature of -1.5 °C was considered to be most appropriate for shelf life of perishable food like meat [MOJE, 1998, JAMES and JAMES, 2002].

2.5.3 Door openings

Several authors noted a heat gain caused by door openings and, concomitant with this, an increased energy use of refrigerators [PEART, 1993, WICKE and BÖHMER, 1998, LEPTHIEN, 2000]. When the door is opened, the cold air inside the compartment is exchanged by warm and moist air from the ambient. SAIDUR et al. [2002] calculated an additional consumption of 9 Wh and 12.4 Wh per door opening for two different appliances. A study by PARKER and STEDMAN [1993] revealed a 9.2 Wh increase in energy consumption per door opening. KAO and KELLY [1996] investigated two different refrigerator-freezers and estimated that each door opening causes an additional consumption of 5 and 7.5 Wh, respectively. LIU et al. [2004] evaluated the effect of 50 door openings of the fresh food compartment of 5 seconds each at an ambient temperature of 15 °C. It was found that each opening increased energy consumption by 5 to 10 %, depending on model of appliance. MEIER [1995] and VHK [2005] considered the impact of door openings on refrigerators' energy use to be negligible due to low heat capacity of the air.

2.5.4 Storage of food

Although the storage of especially warm load is an important factor influencing refrigerators' energy consumption [VHK, 2005], it is objective of only few research activities. According to MASJUKI et al. [2001] and SAIDUR et al. [2000], an additional energy consumption of 90 Wh was generated by storing 1 kg of water of a temperature of 24 to 25 °C. VHK [2005] reported an increase of 4-10 % in yearly energy consumption caused by the storage of 1000 kg of water per year. A study by HASANUZZAMAN et al. [2008] described an additional consumption of 108 Wh/day per kg fresh water.

Owing to a lack of information on the quality and quantity of food stored in domestic refrigerators, it was previously impossible to get more realistic assessments of their impact on refrigerators' energy consumption.

2.5.5 Filling level

Only few studies were found that evaluated the effect of the filling level of refrigerator compartments on energy consumption. BANSAL [2001] investigated the effect of load inside the freezer compartment only, and the effect of load inside both, freezer and fresh food compartment. The freezer compartment of two different refrigerator-freezers was loaded with food packs. The load of fresh food compartment consists of bottles filled with water. After loading, 21 – 23 % of volume was occupied with bottles. In the case of the first appliance, the energy consumption decreases by 3 to 5 % compared to the empty appliance. In the second case, a small raise in energy consumption (12.3 % and 1 %, respectively) was noted. As a consequence, the effect was not assessed to be appreciable. However, several populist sources recommend keeping the refrigerator as full as possible to reduce the amount of energy use.

3 Objective

Domestic refrigerators are one of the largest energy users in private homes in most developed countries and, as such, have become a target for energy efficiency improvements. An approach for improvements was the implementation of the European Energy Label in mid-nineties. On the one hand, its goal is to prompt new technical developments on the part of the manufacturers by intensifying competitive situation. On the other hand, the Energy Label intends to inform consumers about the efficiency of appliances allowing them to make a better-informed purchase decision. Currently, domestic refrigerators' Energy Label test in Europe is carried out at an ambient temperature of 25 °C without door openings. During the test, the fresh food compartment is empty. These test conditions are different from the conditions in most households which is accordingly a frequent point of criticism.

The main objective of this study is the investigation and assessment of refrigerators' energy consumption under realistic working conditions by laboratory tests with special focus on covering the entire consumer relevant area. The factors ambient temperature, daytime temperature variations, internal compartment temperature setting, load, heat load by storing warm products and door openings shall be of particular interest for the present study.

As a first step in the realization of this, the consumer real life behaviour in using their refrigerator in private homes shall be surveyed. The obtained data shall serve in a second step as a basis for designing and implementation of laboratory experiments. Based on the laboratory results, a simulation model that allows predicting refrigerators' energy consumption under real life conditions with minimal experimental expenditure shall be derived in a third step. The focus here is on the universal application for different kinds of appliances and on covering the entire consumer relevant range.

Finally, the model shall be validated by comparing the theoretically calculated energy consumption with experimental data obtained in different series of laboratory tests.

4 Material and Methods

The methodological procedure used in the present study consists of four consecutive steps as shown in Figure 4-1.

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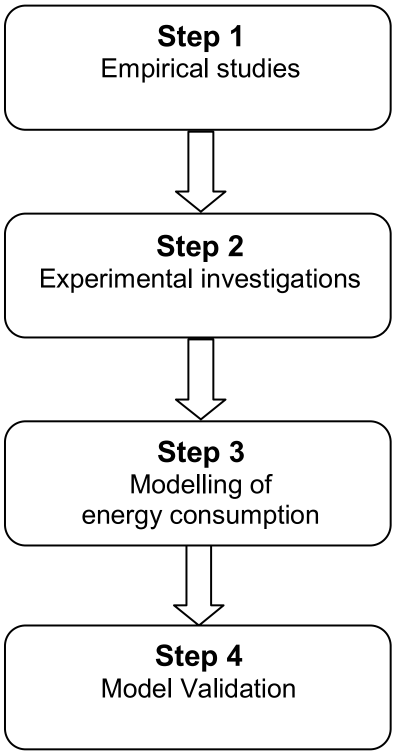

Figure 4-1: Overview of the modelling procedure

In a first step, the consumer's real life behaviour in using their domestic refrigerator and the ambient conditions in the domestic environment were analysed in four European countries. For this purpose, two different methods of collecting data were applied to two different samples:

- The first sample contained 1000 households that participated in an online survey. This method should provide a general overview of the conditions in private homes like the place of installation of the refrigerators, the ambient temperature and the internal temperature setting.

- The second method was a so called in-home study with a sample size of 100 households. The main aim of this study was to gain knowledge of loading and unloading patterns of foodstuffs and the behaviour in handling chilled food.

After the field phase, actual ambient conditions and typical behavioural pattern of consumers were extracted from the data gained by the consumer studies.
The response of domestic refrigerators' energy consumption to varying ambient conditions and usage behaviour was examined in various sets of laboratory experiments at a second stage. The experiments were designed following the conditions and the typical behavioural patterns of consumers determined in the first step.
At stage three, the main focus was on the development and adjustment of a simplified model for predicting the energy consumption of domestic refrigerators at actual working conditions.
In the final step, further experiments were conducted to validate the results predicted by the modelling approach.

The following subchapters provide a more detailed description of the steps shown in Figure 4-1.

4.1 Empirical studies

4.1.1 Online survey

A web-based study was conducted to gather information about consumer habits in relation to refrigerator use and refrigerator characteristics.
The online study was carried out in equal shares in four Western European countries namely France, Germany, Great Britain and Spain. A total of 1.011 households participated in the study. Quota sampling was applied to select the participants [MAYER, 2006]. Five equal sized segments with regard to age and household structure

were generated in order to gather differences in use conditions of refrigerators. The presettings for the recruitment are shown in Table 4-1. Only the person who is primarily responsible for purchases and food preparation was asked to fill in the questionnaire.

Table 4-1: Presettings for the recruitment

Household type	Age of household members	No. of households per country
Young single household	Up to the age of 30 years	50
Older single household	At least 55 years of age	50
Couple/ 2 person household	No presetting	50
Household with 3 or 4 persons	No presetting	50
Families with at least 5 persons	No presetting	50

A standardized questionnaire containing 41 closed and 2 semi-open questions was applied in order to facilitate the data analysis. A convenience sample of 15 households pre-tested the questionnaire to identify the time required to complete the questions and to ensure the clarity.

The survey was conducted as an online study. Advantages of this medium are short field times to obtain the needed completed questionnaires and a largely automated data collection [BATINIC, 2000]. On the other hand, using the internet for surveys limits the population to those with internet access (currently 60-70 % in western European countries) [BANDILLA et al., 2001, INTERNET WORLD STATS, 2010]. This is the major disadvantage of the method.

The participants were obtained by a German market research company (ODC Services, GmbH, Munich) with access to a huge number of European panellists. This company additionally hosted the survey and ensured expedient replies. The questionnaire was sent as a link via email to a random selection of 10.000 registered panellists in accordance with the predetermined quota. The survey was closed as soon as the objective of 1000 completed questionnaires was achieved.

4.1.2 In-home study

An in-home study (n=100) was carried out between spring 2008 and spring 2009. The participants were randomly selected by two different German market research companies (ODC Services GmbH, Munich and Toluna Germany GmbH, Frankfurt) and invited to take part in the study. In order to make this study comparable with the online survey, the same quotation was applied to select the participants. A participant recruiting screening questionnaire was designed in order to make sure that participating persons comply with the predetermined criteria and quotation. All selected households that agreed to participate in the study were visited to brief the participants and to deliver the required equipment like diaries and temperature data logger. After finishing the survey, the equipment was personally collected or sent back by the participants.

The in-home study consists of three different parts:

4.1.2.1 Temperature survey

A temperature data logger (EasyLog-USB-1, Lascar Electronics), adjusted to record the internal refrigerator temperature every minute for a period of 11 days, was placed centrally on the middle shelf of each refrigerator. The logged data were downloaded via the provided configuration software EL-WIN-USB and exported to Microsoft Excel 2007.

4.1.2.2 Diary surveys

All participating households were asked to fill in two different diaries for a period of fourteen consecutive days. Pre-printed forms were provided to the participants in order to facilitate the recording process in participants’ homes as well as the subsequent data analysis. These forms contained twenty predetermined product groups of food. The classification of these product groups was mainly developed referring to the systematic index of incomes and expenses of private households, a system of the Federal Statistical Office of Germany [STATISTISCHES BUNDESAMT, 1998]. In the storage diary, the quantity of all food that was put inside the refrigerator should be registered, sorted by date. The consumption diary contained fourteen pages, one for every day. In this diary, the quantity of all food, which was removed from the refrigerator, should be recorded, sorted by time of day and product group of the food. The quantities should be registered using common household measures or metric units.

In preparation for data analysis, all data expressed in common household measures were converted into metric units using two conversion tables [DINAUER et al., 2009, NESTLÉ DEUTSCHLAND AG, 2006].

4.1.2.3 Pictures

In addition to the diaries, the participants were asked to take every day at least two photos of their refrigerator, one of the internal chiller compartment and one from inside the door. If special compartments, like the crisper, were covered by shelves or other items, the participants were asked to take additional pictures to make all parts of the internal space visible.

An easy to handle digital camera was provided to each participant for the duration of the study.

The main purpose of these photos was to examine the use of refrigerators' net volume. Moreover, they provide a way to validate the data recorded by means of the diaries.

4.1.3 Data analysis

Data were analysed using the Statistical Package for the Social Sciences (SPSS Inc, Chicago, IL), version 14. Frequency distributions were computed for nominally scaled data. Ordinal and metric data provide opportunities for in-depth statistical analyses.

Besides the computation of measures of location (e.g. arithmetic mean and median) and measures of dispersion (e.g. standard deviation and percentiles), the ordinal and metric data were tested for significant differences. For this purpose, they were examined for normality of the distribution using the Kolmogorov-Smirnov-test. Depending on the scale level, the distribution, the degree of dependence of the data and the number of samples, one of the following statistical tests was used (Table 4-2).

Table 4-2: Statistical tests for significant differences [own source based on ZÖFEL, 2000]

Scale level	**Distribution**	**No. of samples**	**Degree of dependence**	**Test**
Interval scale	Normal	2	Independent sample	Student's t-test
Interval scale	Normal	2	Paired sample	Paired-samples t-test
Interval scale	Normal	> 2	Independent sample	One-way analysis of variance (ANOVA)
Interval scale	Normal	> 2	Paired sample	One-way repeated measures ANOVA
Ordinal scale	(Not) normal	2	Independent sample	Mann-Whitney U test
Interval scale	Not normal	2	Independent sample	Mann-Whitney U test
Ordinal scale	(Not) normal	2	Paired sample	Wilcoxon test
Interval scale	Not normal	2	Paired sample	Wilcoxon test
Ordinal scale	(Not) normal	> 2	Independent sample	Kruskal-Wallis H test
Interval scale	Not normal	> 2	Independent sample	Kruskal-Wallis H test
Ordinal scale	(Not) normal	> 2	Paired sample	Friedman-test
Interval scale	Not normal	> 2	Paired sample	Friedman-test

The level of significance was defined as follows:

- $p > 0.05$ not significant
- $p \leq 0.05$ significant
- $p \leq 0.01$ highly significant
- $p \leq 0.001$ very highly significant

The results are presented by means of bar and pie charts. For metric data, histograms or Box Whisker plots showing minimal and maximal observations, lower quartile, median and upper quartile are used.

4.2 Determination of actual conditions and consumer behaviour

Results gained from the consumer studies were primarily used to set up the test conditions for the laboratory experiments. These test conditions should reflect actual ambient conditions and usage behaviour of refrigerators in private homes. Usage conditions of at least 90 % of all consumers in the relevant countries should be covered by the laboratory tests, extreme conditions were not considered. In accordance to literature [SAIDUR et al., 2002, MEIER, 1995, LEPTHIEN, 2000], the factors ambient temperature, internal compartment temperature, filling level, door openings and placement of warm food were of particular interest.

The relevant range of ambient temperature was determined using the results of the online survey. The upper and lower limit of the range are based on the results regarding the minimum and the maximum ambient temperature, respectively.

The results of the online survey also provided a basis for the determination of actual internal compartment temperatures and actual frequencies of daily door openings. The average duration of door openings, however, was deduced from the study by THOMAS [2007].

The ascertained filling levels of domestic refrigerators rest upon a visual assessment of the digital pictures made during the in-home study.

For determining the amount of additional heat load caused by the storage of products, several data like the mass of the product, its specific heat capacity and its temperature were necessary. The amount of heat load per product (*Q*) can be calculated using equation 4-1.

$$Q = m \cdot c \cdot \Delta\vartheta \qquad (4\text{-}1)$$

m = mass of product, c = specific heat capacity of the product, $\Delta\vartheta$ = difference between the temperature, at which a product is placed into the refrigerator and the internal refrigerator temperature

The mass *m* of products stored in the refrigerator after a purchase could be deduced from the storage diaries (see also Chapter 4.1.2.2). The specific heat capacities of the products were taken from an online database [THE ENGINEERING TOOLBOX, 2009]. The temperatures recorded by the data logger during the in-home study (see also Chapter 4.1.2.1) were used as a basis for determining the internal temperatures of refrigerators. For determining the temperature, at which a product is placed into the refrigerator, several assumptions had to be made:

1. Foodstuff can be differentiated into two different groups (cf. Table 4-3). Whereas the first group comprises the foodstuff that is ordinarily stored at ambient temperature in retail stores, the second group consists of chilled products.
2. Products of the first group are placed into the refrigerator at a temperature of 22 °C.
3. Chilled products are unprotected against heat after removal from cold storage and during the transport from the retail store to the home. Consequently, they are exposed to ambient temperatures all the time.

Table 4-3: Differentiation of foodstuffs according to their storage temperature in retail store

Products stored at ambient temperature	**Chilled products**
Beverages	Meat
Homogenised milk and cream	Cold meat
Fruits, vegetables, salads	Fish
Jam and honey	Butter, margarine, spreadable fat
Chocolate and nut spread	Cheese
Eggs	Curd cheese, cream cheese
Ketchup, mustard, sauces, dips	Yogurt, pudding, flummery
Bread, cake, pastries	
Convenience foods	

The temperature ϑ, at which a chilled product is placed into the domestic refrigerator, was calculated according to the Newton's law of cooling (equation 4-2):

$$\vartheta = \vartheta_a + (\vartheta_0 - \vartheta_a) \cdot e^{-k \cdot t} \qquad (4\text{-}2)$$

ϑ = temperature, at which a product is placed into the refrigerator, ϑ_a = ambient temperature during transport, ϑ_0 = initial temperature of a chilled product at the time of removal from refrigerated counter, k = constant dependent on the material properties of the product and its packing, t = time lapse from refrigerated counter to the domestic refrigerator

In order to enable a calculation of the equation above, different scenarios had to be generated concerning the ambient temperature during transport. These scenarios are based on country-specific climate data [AGENCIA ESTATAL DE METEOROLOGÍA, 2009, DEUTSCHER WETTERDIENST, 2009] and are aimed at covering a wide range of situations (see also Table 4-4).

Table 4-4: Scenarios of ambient temperature in different countries

	France	**Germany**	**Great Britain**	**Spain**
Scenario 1: Minimal temperature	2 °C	- 1 °C	1 °C	3 °C
Scenario 2: Normal temperature	13 °C	11 °C	11 °C	15 °C
Scenario 3: Maximal temperature	35 °C	30 °C	30 °C	45 °C

The initial temperature of a chilled product ϑ_0 is assumed to be equivalent to the ideal storage temperature in retail stores (2 °C).

Further on, the material constant k of the different products was required to calculate the equation. Because these values are lacking in literature, they had to be determined in laboratory tests. For this purpose, several items of each product class, representing the whole spectrum of commercially available chilled products and their packing, were investigated under climatically controlled conditions. Starting at an initial core temperature of 2 °C, each product was stored at a constant room temperature of 22 °C over a period of at least one hour. During this time lapse, the increase of temperature was measured and recorded using a core temperature probe. Finally, the equation 4-2 was rearranged to solve for the material constant k. Table 4-5 provides an overview of the average k-values of each product group that were used for further calculations.

Based on the results of THOMAS [2007], the time lapse t from refrigerated counter to the domestic refrigerator is assumed to be between 30 and 90 minutes.

The total amount of additional heat load, caused by the storage of food after purchase, was calculated by summing up the amount of heat load of each product placed into the refrigerator.

Table 4-5: Average *k*-values of different packed product groups

Product	**Measured k -value in 1/min**
Meat	-0.010
Cold meat	-0.026
Fish	-0.046
Butter, margarine, spreadable fat	-0.009
Cheese	-0.017
Curd cheese, cream cheese	-0.007
Yogurt, pudding, flummery	-0.011

4.3 Laboratory experiments

4.3.1 Experimental set-up

All laboratory experiments were carried out with four different commercially available domestic refrigerators. Figure 4-2 gives an overview of the appliances used in the experiments. Besides the net volume of each compartment and the type of cooling system, also the energy efficiency class and the lowest and highest possible internal temperature setting are given.

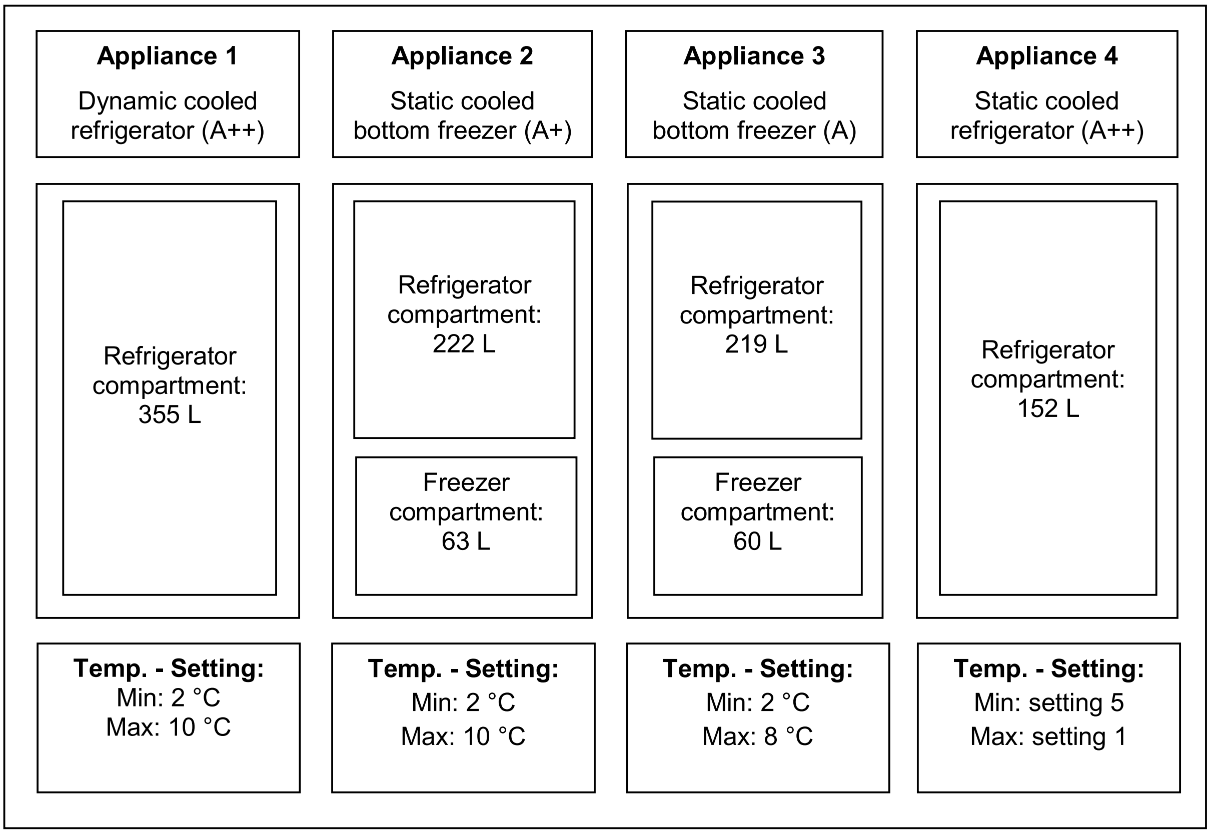

Figure 4-2: Overview of tested refrigerators

Table 4-6 shows the applied equipment that was used to carry out the laboratory test.

Table 4-6: Overview of applied materials

Equipment	Specification
Climatically controlled chamber	Height x width x depth 2.45 m x 5 m 2.35 m, temperature infinitely adjustable between 4.7 and 40 °C
Computer-based measurement device	*Elcontrol Energy VIP 96* Manufacturer: SLG Prüf- und Zertifizierungs GmbH, Hartmannsdorf, Germany
Power meter	Mains voltage 200-260 V, 10 impulses/ Wh Manufacturer: SLG Prüf- und Zertifizierungs GmbH
Software	AMR Wincontrol Manufacturer: akrobit® software GmbH, Gera, Germany Microsoft Office Excel 2003/2007
Thermocouples	Type: Special THL TX 2 x 0.30 mm² Alloy: TNX Temperature range: -40°C / +70°C Manufacturer: SAB BRÖCKSKES GmbH & Co. KG, Viersen, Germany
ALMEMO® input connection plugs for thermocouples type T (Cu-CuNi)	Measuring range: -200 to +400 °C Resolution: 0.1 K Ord. no.: ZA 9021−FST Manufacturer: Ahlborn Mess- und Regelungstechnik GmbH, Holzkirchen, Germany
Monopods including holder for brass cylinder	Height: 5 to 20 cm Vertically adjustable Supplier: own production
ALMEMO® D measuring module for humidity and temperature including Almemo® connecting cable and Almemo® input connection plugs	Humidity measuring range: 0 to 100 % RH Accuracy at 23 °C: ±0.8% RH Temperature measuring range: -50 to +100 °C Accuracy at 23 °C: ±0.1 K Ord. no.: FHAD36RSL05 Manufacturer: Ahlborn Mess- und Regelungstechnik GmbH, Holzkirchen, Germany
Tripod including bracket for ALMEMO® D measuring module	Height: 1.20 m Height-adjustable Supplier: own production
Test enclosure	Dull black-painted, made of 20 mm thick plywood 20 mm Supplier: own production in conformity with EN ISO 15502:2005
Brass cylinder	Mass: 25 g ± 5 % Minimum external area (diameter = height = about 15.2 mm) Supplier: own production in compliance with EN ISO 15502:2005

Test packages for freezing trials	0.5 kg and 1 kg packages Dimensions/ masses: 50 x 100 x 100 mm/ 500 g 50 x 100 x 200 mm/ 1000 g Composition: - 23.0 % Oxy-ethyl-methyl-cellulose - 76.42 % Water - 0.5 % Sodium chloride - 0.08 % 6-chloro-m-cresol (in conformity with EN ISO 15502:2005) Manufacturer: Frigor Gime, Siena, Italy
PET-bottles filled with mains water	Capacity: 0.5 L, 1 L, 1.5 L Supplier: Food retailing market
Voltage stabilizer	Typ MSEG 2.5; 2500 VA, 230 V ± 10 %, cos Θ = 1

All laboratory experiments were carried out under controlled conditions in a climatically controlled chamber. This chamber is located in the material testing laboratory at the Institute of Agricultural Engineering in Bonn.

The energy consumption tests were largely conducted following the European standard for household refrigerating appliances EN ISO 15502:2005. According to this standard, both fridge-freezers (appliance 2 and 3) intended for building-in were installed into a dull black-painted test enclosure made of 20 mm thick plywood. The dynamically cooled refrigerator (appliance 1) and the statically cooled refrigerator (appliance 4) were set up planar on the floor of the climatically controlled chamber.

Experimental data like internal compartment temperatures (°C), ambient temperature (°C), ambient humidity (% RH), refrigerator's energy consumption (Wh), power (W), voltage (V) and current (A) were recorded using the measuring device *Elcontrol Energy VIP 96* and the corresponding software *AMR WINControl.* Experimental data were logged every minute.

In order to enable the exact recording of even small amounts of energy consumption, such as in standby mode, an external power meter with higher resolution was inserted between refrigerator's main plug and measurement device. This power meter adds up the consumed energy internally and output one pulse signal per 0.1 Wh of consumed energy.

The refrigerating appliances were tested at a voltage of 230 V ± 1 % and a frequency of 50 Hz ± 1 % by using a voltage stabilizer on the mains supply.

A combined humidity/ temperature measurement module fixed on a tripod at a height of 1 m was used to determine the ambient temperature as well as the ambient humidity. The sensor was shielded from any radiant heat, including air conditioning equipment, doors and other appliances.

The internal air temperature in the fresh food compartment was measured in accordance with the standard EN 15502:2005 using type T (copper-constantan) thermocouples inserted in a brass cylinder. The brass cylinders including the thermo sensors were affixed on specific temperature measurement points (T1, T2 and T3, see also Figure 4-3) in the fresh-food storage compartment by use of height-adjustable monopods. The monopods were secured against shifting using magnetic tape.

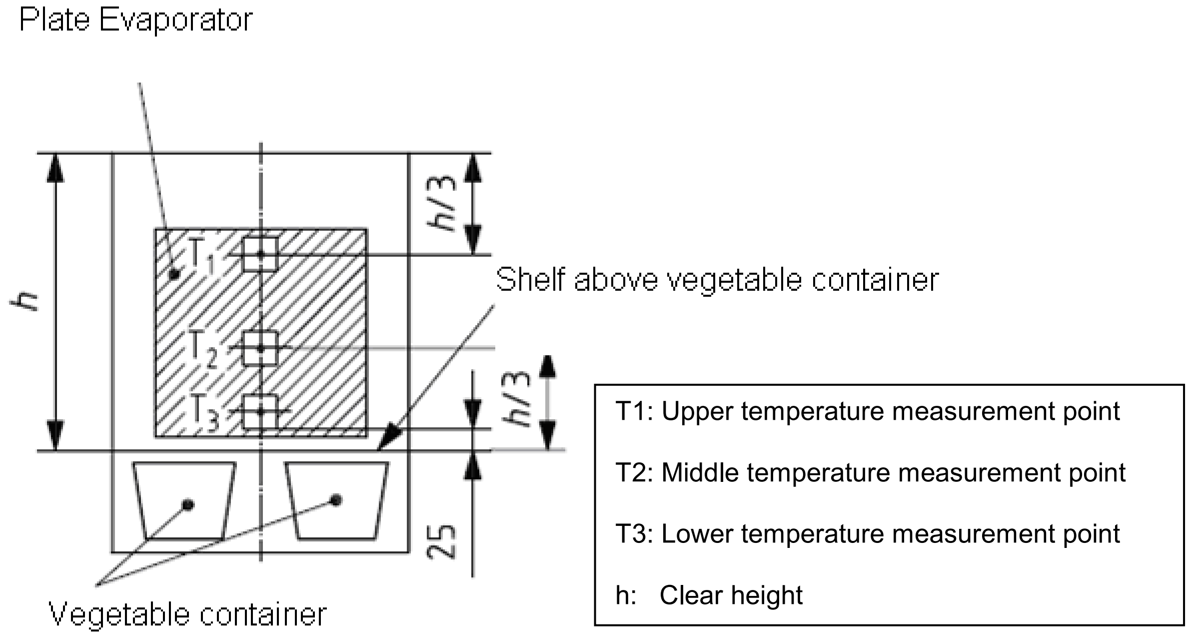

Figure 4-3: Temperature measurement points [Source: standard EN 15502:2005, modified]

In accordance with the standard, the sensors were centrally (half the length, half the width and half the depth of the compartment) installed at each temperature measurement point. The lower probe (T3) was fixed at a height of 25 cm, measured from the bottom of the fresh food compartment. The middle sensor (T2) was positioned at a distance of one third of the clear height above the shelf above the vegetable container. The upper probe (T1) was installed at a distance of one third of clear height from the top of the fresh food compartment. The connecting cable between thermo sensor and measuring device was arranged to prevent air leakage into the food storage compartment. For that purpose, the door seal on the cable exit was reinforced with putty.

So called test packages and PET bottles filled with water were used as food simulants. The test packages' composition and their dimensions and masses are shown in Table 4-6. In conformity to the standard EN 15502:20005, their thermal characteristics correspond to those of lean beef and their freezing point is -1 °C. Some of the 500 g packages were slightly modified and used as so called M-packages so as to measure food storage temperatures. They were equipped with a thermocouple inserted in the geometrical centre of the package. In order to minimize extrinsic heat conduction, the cable exit on the test package was sealed with a tape. The PET bottles were filled with 0.5 l, 1 l and 1.5 l of mains water, respectively and their lids were screwed down tightly. Some of the 1.5 l bottles were also equipped with thermocouples to enable temperature measurements in liquids. For that purpose, a small hole was drilled into the bottle lid and the thermocouples were inserted into the centre of the bottle.

The appliances were evenly loaded with packages, M-packages and bottles. After loading, the respective target temperature of the internal compartment was adjusted and the door was closed tightly.

After respective preparation, the appliances had to obtain stable operating conditions in order to ensure equal preconditions for all experiments. According to the standard EN 15502:2005, stable operating conditions are defined as conditions, in which energy consumption as well as appliances' mean temperatures are stable. These conditions are attained when the refrigerators were operated for a certain period without changing internal and external temperatures and when the energy consumption is not differing by more than 3 % in each operating cycle during a period of 4 hours (empty state) or 6 hours (loaded state). Furthermore, up- or downward trends in storage temperatures, other than amplitudes in consequence of normal temperature regulation, have not to be recognisable.

After attaining stable operating conditions, each experiment started at the beginning of an operating cycle in accordance with the standard DIN EN 15502:2005. An operating cycle is defined as a period commencing when the compressor of the refrigerator starts up and terminating at the moment before the compressor starts up for the next time. The duration of each test period was at least 24 hours and consisted of a whole number of operating cycles.

4.3.2 Design of experiments

In order to investigate systematically the influence of consumer behaviour on energy consumption of refrigerating appliances, three different experimental series were designed based on a three level Box-Behnken design with two replications at the centerpoint. The Box-Behnken design is a response surface design. The experimental points lie on the midpoints of the edges of the process space and additionally in the centre as exemplified for a three-factor design in Figure 4-4. The design is derived from 3^n-full factorial designs by reduction and requires three levels of each factor. [OTTO, 2007, NIST/SEMATECH, 2010]

It enables to investigate and reveal quadratic effects and 2-factor interactions [KLEPPMANN, 2008]. If two replications are performed at the centerpoint of the three-factor design, the total number of experiments is 15 compared to 27 experiments with the full factorial design.

The influences of the factors ambient temperature (static), ambient temperature with diurnal variations, internal temperature setting, load and heat load on refrigerators' energy consumption were investigated during the study. The ranges of all factors were based on real consumer behaviour obtained by the consumer studies (see also chapter 4.2).

The experimental series were designed as follows.

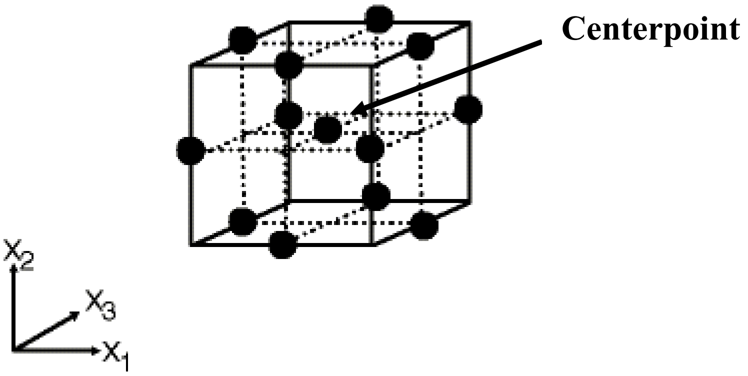

Figure 4-4: Box-Behnken Design for three factors [source: www.versuchsmethodik.de, 2001]

4.3.2.1 Experimental series under static conditions

In this series of experiments, the influences of the factors ambient temperature, internal temperature setting and load on refrigerators' energy consumption were investigated. The aforementioned factors remained unchanged during an experiment. Consequently, this experimental series simulated static conditions in a household in which the cooling appliance operates without active involvement of the consumer.

In accordance to the findings of the consumer studies, the ambient temperature was varied within the range 5 to 40 °C and the internal temperature between the lowest and highest possible temperature setting. The influence of the load was investigated within the range 0 to 25 % of refrigerator's net volume.

As described above, the experimental design requires three level of each factor. Using the software program Design Expert (Stat-Ease Inc., Minneapolis) the experimental design was obtained for the series under static conditions.

4.3.2.2 Experimental series under diurnal ambient conditions

In this experimental series diurnal temperature variations were simulated. The ambient temperature was varied between 0 and 35 K pending on the initial temperature.

However, a maximum temperature of 40 °C should not be exceeded within an experiment, since this condition is not likely to be found in households.

The simulated temperature profiles may also arise in households, for example if the appliance is placed in an unheated room, where the temperature extensively follows the external ambient temperature. The objective of this series was to investigate the influence of fast changing ambient temperatures on refrigerators' energy consumption. Besides the diurnal temperature variation, also the initial ambient temperature and the internal temperature setting were included as further factors in this experimental series. Additionally, the influence of refrigerators' load on energy consumption was tested within this series. For this reason, all experiments were carried out two times using appliances with 0 % and 12.5 % of load. Due to the complexity of the experiments of this series, only appliance 1 and 2 were tested.

In order to ensure repeatability as well as comparability within the series and among the different experimental series, the test procedure had to be standardised. For this purpose, all experiments of this series followed the same pattern as shown in Figure 4-5. At the beginning, the initial temperature was kept constant over a period of two hours. This period was followed by a period of 4 hours, in which the temperature rose to its maximum in a steady manner. Subsequently, the maximum temperature was kept constant for 12 hours before it decreased equally to its initial value over a period of another four hours. At the end of each experiment, like in the beginning, the initial temperature was maintained at a constant level for two hours.

Figure 4-5 shows the five aforementioned described phases for different initial temperatures and different factor combinations.

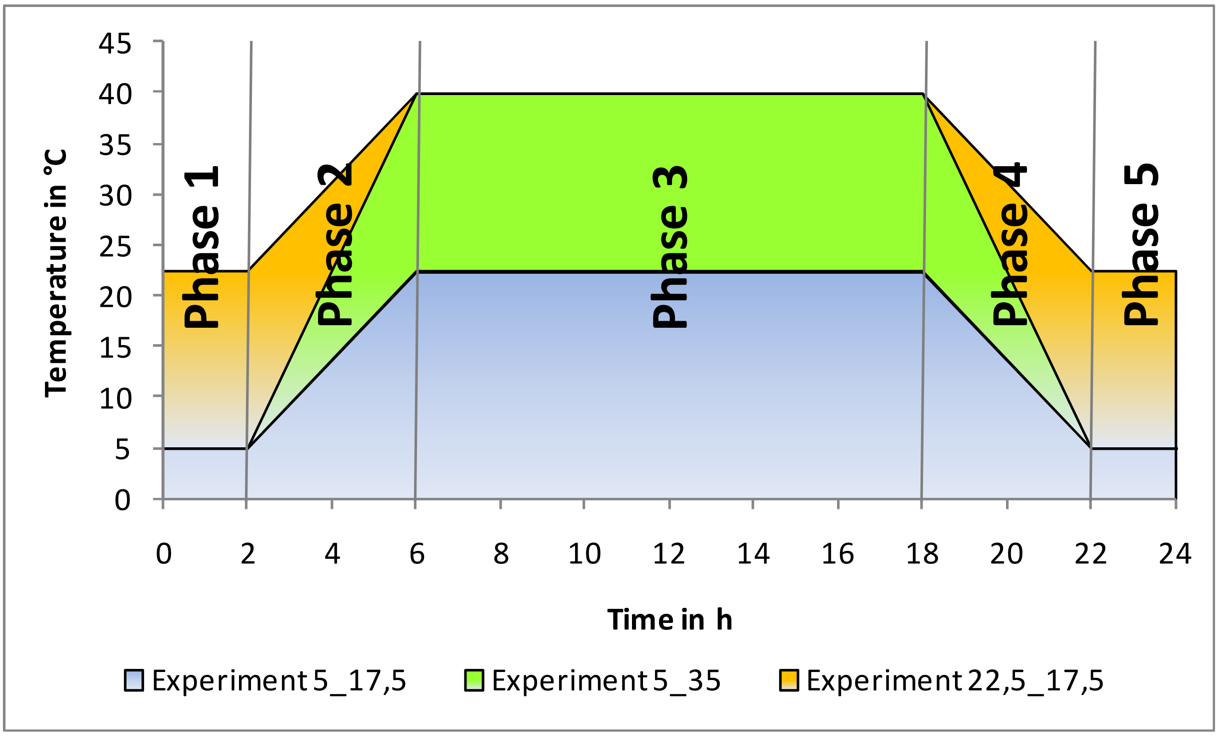

Figure 4-5 Simulated diurnal temperature profiles
(The first number of the legend specifies the initial temperature in °C of the respective experiment. The second number shows the temperature variation in K.)

Also for this experimental series, a three level Box-Behnken design was used.

4.3.2.3 Experimental series under dynamic conditions

In this series of experiments, the influences of the factors ambient temperature, internal temperature setting and heat load on refrigerators' energy consumption were investigated. In contrast to the static series, the test conditions were changed during the experimental procedure. An additional heat load, for example by placement of hot items or purchased foodstuffs, was simulated. Thus, the active involvement of the consumers was considered in addition to the ambient conditions.
In compliance with the experiments under static conditions, the ambient temperature was varied within the range 5 to 40 °C and the internal temperature adjustment between the lowest and highest possible temperature setting. In order to simulate real consumer behaviour at the best, the influence of a heat load of 300 to 1000 kJ, derived from the results of the consumer studies as described in chapter 4.2, was additionally investigated. The influence of refrigerators' load on energy consumption was not

tested within this series. For this reason, all experiments were carried out using an initial load of 12.5 % of refrigerators' net volume.

For the purpose of repeatability as well as comparability within the series, all experiments of this series followed the same pattern. At the beginning of each experiment, the initial conditions were kept constantly for two hours. After this period, the refrigerator's door was opened for exactly one minute at an angle of 90 degree and the respective heat load was placed. This heat load resulted from the insertion of a corresponding quantity of test packages and water bottles in a ratio of 3:2. They were homogenously distributed within the cooling compartment. The temperature of the packages and bottles was brought previously to a temperature of 22 °C. After insertion, the door was closed tightly and the experiment went on for another 22 hours without further changes of test conditions. Analogous to all other experimental series, the test period of each experiment was at least 24 hours.

4.3.2.4 Experiments testing the influence of door openings

Additionally to the experiments described above, the influence of door openings on refrigerators energy consumption was analysed. During the test period of at least 24 hours, the door was opened 36 times at an angle of 90 °, while all other parameters like the ambient temperature, the refrigerator's load and the internal compartment temperature were kept constant. The door remained open for 15 s each time. In order to ensure repeatability and comparability, all experiments followed the same pattern shown in Figure 4-6.

At the beginning of each experiment, the initial conditions were kept constantly for two hours. After this period, the refrigerator's door was opened for exactly 15 s at an angle of 90 degree. This opening process was repeated every 10 minutes over a period of 3 h. After that, the door remained closed for 12 h. This period was followed by another door opening period. The door was opened again for further 18 times during a period of 3 h. At the end of each experiment, the refrigerators' doors were kept closed for at least four hours.

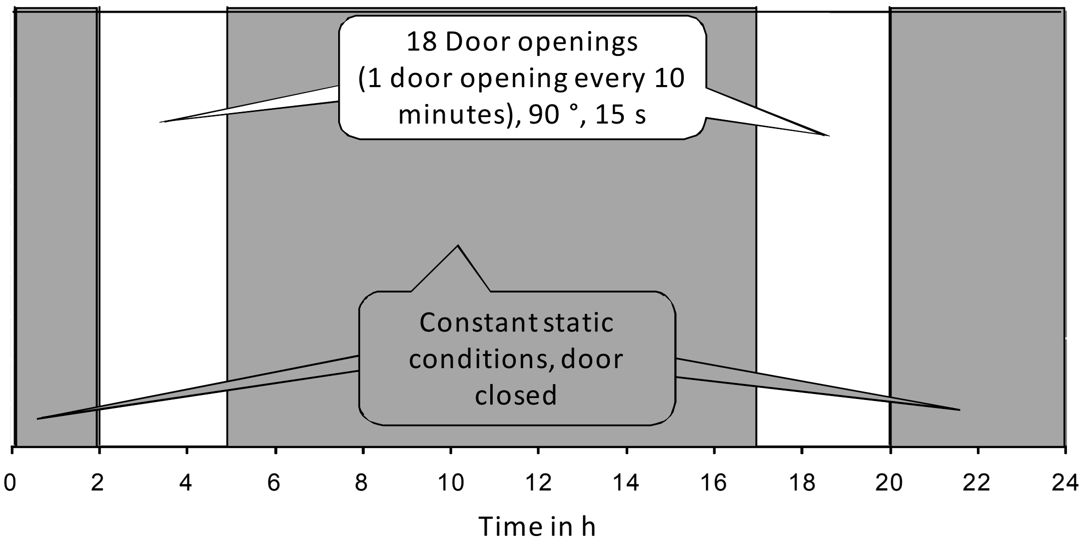

Figure 4-6: Procedure of experiments with door openings

The influence of door openings on refrigerators' energy consumption was tested at an ambient temperature of 22.5 °C and 40 °C. The internal compartment temperature was adjusted to 6 °C and 12.5 % of refrigerator's net volume was filled. These tests were performed with the appliances 1 and 2.

4.3.3 Analysis of experimental data

The Design Expert software was also used for data analysis. First of all, the correlation between the dependent variable (response) and the independent variables (input factors) were investigated using the Multi Linear Regression (MLR) method. This method aims to compute the coefficients of the model to minimise the sum of squares of the residuals. A second-order polynomial (equation 4-3) was fitted to the experimental data. Considering all of the linear and square terms and linear by linear interactions, the quadratic response model can be described as follows [BÜHL, 2008]:

$$Y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_{ii}^2 + \sum \beta_{ij} x_i x_j + \varepsilon \tag{4-3}$$

Y = response, β_0 = constant, β_i, β_{ii}, β_{ij} = coefficients of regression representing the effects of the respective variable, x_i, x_{ii}, x_j = input factors, ε = residual error

Starting from a full quadratic model, an iterative fitting process was used. Each coefficient was tested for significance. Insignificant terms were removed from the equation. These processes were repeated until there are no insignificant terms.

In a next step, Analysis of Variance (ANOVA) was performed to verify and validate the model. Sequential F-test, lack of fit test and further adequacy measures like the coefficient of determination (R^2), the adjusted R^2, the predicted R^2 and adequate precision ratio were used to examine the statistical significance of the model and of each term. The probability (p-value or Prob>F) was calculated by means of the ANOVA. Values of 0.05 or less indicate statistical significance. [DESIGN EXPERT SOFTWARE, 2005, BÜHL, 2008]

The lack of fit test compares the variation within replications with model dependent variations. This test decomposes the residual error into two different parts. The first part is due to pure error that means variations of replications around their mean value. The second part is due to variation of the mean values around the model prediction. The lack of fit will be significant, if the model does not fit the data well. [SAS INSTITUTE INC., 2011]

The coefficient of determination (R^2) measures the proportion of variation explained by the model relative to the mean. It is the ratio of the regression sum of squares to the total sum of squares (equation 4-4). [ANDERSON AND WHITCOMB, 2005, RELIA SOFT CORPORATION, 2008]

$$R^2 = 1 - \left(\frac{SS_R}{SS_M + SS_R} \right) \tag{4-4}$$

R^2 = Coefficient of determination, SS_R = Residual sum of square, SS_M = Mean sum of square

The adjusted R^2 (equation 4-5) also is an estimate of the fraction of overall variation in the data accounted for in the model. However, it is adjusted for the number of terms in the model relative to the number of points in the design. [ANDERSON and WHITCOMB, 2000]

$$R^2_{adjust.} = 1 - \left[\left(\frac{SS_R}{df_R} \right) \cdot \left(\frac{SS_R + SS_M}{df_R + df_M} \right)^{-1} \right] \tag{4-5}$$

$R^2_{adjust.}$ = adjusted R², SS_R = Residual sum of square, SS_M = Mean sum of square, df_R = Residual degrees of freedom, df_M =Model degrees of freedom

The purpose of the predicted R² (equation 4-6) is to measure how well the model predicts responses for new observations. For its calculation, each observation is systematically removed from the data set. Following, a regression equation is estimated and the model's quality of prediction of the removed observation is determined [MINITAB, 2010]:

$$R^2_{pred.} = 1 - \left(\frac{PRESS}{SS_R + SS_M} \right) \tag{4-6}$$

$R^2_{pred.}$ = predicted R², $PRESS$ = Predicted residual error sum of squares, SS_R = Residual sum of square, SS_M = Mean sum of square

The adequate precision (equation 4-7) is a signal to noise ratio that compares the range of the predicted values at the design points to the average prediction error. Ratios greater than 4 indicate adequate model discrimination [INFORMATION ENGINEERING AND SYSTEMS LABORATORY, 2011]:

$$Adeq.precision = \left[\frac{\max(\hat{Y}) - \min(\hat{Y})}{\sqrt{\frac{p\sigma^2}{n}}} \right] \tag{4-7}$$

Adeq.precision = Adequate precision, p = Number of model parameter including intercept β_0, σ^2 = Residual mean square from the ANOVA table, n= Number of experiments, Ŷ= Predicted values

Moreover, the Design Expert software was used to determine which factor influences the response and to compare the strength of this effect. Factor effects on the response were presented by means of different plots such as interaction graphs, perturbation plots and 3D-graphs.

4.4 Model development

A simplified semi-empirical model to predict refrigerators' energy consumption under real life conditions was developed. The model bases on first-principle algebraic equations adjusted with experimental data obtained from laboratory studies.

The selected modelling approach is based on the equation to calculate the work input required for a Carnot refrigerator (equation 4-8). This equation can be derived from equation 2-1, which describes the coefficient of performance of a Carnot refrigerator:

$$Work_{input}^{CR} = \frac{T_H - T_L}{T_L} \cdot Heat_{absorbed} \tag{4-8}$$

where T_L is the temperature of the lower isotherm and T_H the temperature of the higher isotherm.

It is assumed that the absorbed heat is dependent on the heat flux per unit area and per unit time (equation 2-2) and on any additional heat load Q_{input}:

$$Heat_{absorbed} = \lambda \cdot A \frac{T_{out} - T_{in}}{\Delta\delta} \cdot \Delta t + Q_{input} \tag{4-9}$$

where λ is the thermal conductivity in $W \cdot K^{-1} \cdot m^{-1}$, A is the surface area of the refrigerator in m^2, $\Delta\delta$ is the distance between the two ends of the refrigerator wall in m, T_{out} is the ambient temperature in K and T_{in} the temperature inside the refrigerator in K.

So, equation 4-8 can be written as:

$$Work_{input}^{CR} = \frac{T_H - T_L}{T_L} \cdot \left[(T_{out} - T_{in}) \cdot a \cdot \Delta t + Q_{input} \right] \tag{4-10}$$

where the constant term $\frac{\lambda \cdot A}{\Delta \delta}$ is substituted by a for reasons of simplicity.

For the purpose of simplification, it was assumed that there is a constant offset x between T_H and T_{out} on the one hand and a constant offset y between T_L and T_{in} on the other hand, meaning that the actual temperature, where the condensation takes place, is higher as the ambient temperature and the actual temperature, where the evaporation takes place, is lower as the internal compartment temperature.

$$T_H = T_{out} + x \tag{4-11}$$

$$T_L = T_{in} - y \tag{4-12}$$

Using equations 4-11 and 4-12 leads to the following equation:

$$Work_{input}^{CR} = \frac{(T_{out} + x) - (T_{in} - y)}{(T_{in} - y)} \cdot \left[(T_{out} - T_{in}) \cdot a \cdot \Delta t + Q_{input} \right] \tag{4-13}$$

This simplified equation serves for calculating the work input required for Carnot refrigerators. Domestic refrigerators, however, are based on the vapour-compression refrigeration principle. This principle deviates in some points from the principle of the reversed Carnot refrigeration (cf. 2.2.2). Taking the differences between the two principles into account, equation 4-13 has to be slightly modified so that it can be applied to actual refrigerators. A main difference between the Carnot and the actual vapour-compression refrigeration cycle is the occurrence of heat losses to the surroundings in the actual process. These heat losses, amongst others, lead to a decreased efficiency of the actual process, which can be expressed by an efficiency factor η^*. A further difference between both cycles is that the actual one not only consumes energy during the compressor on-cycle but also during the off-cycle. Taking these differences into account, equation 4-13 is modified into:

$$Work_{input}^{actual} = \frac{(T_{out}+x)-(T_{in}-y)}{(T_{in}-y)} \cdot \left[(T_{out}-T_{in}) \cdot a \cdot \Delta t + Q_{input}\right] \cdot \frac{1}{\eta *} + P_{off} \cdot \Delta t \quad (4\text{-}14)$$

where P_{off} is the power consumption during the compressor off-cycle, which is assumed to be a product-specific constant.

In actual refrigeration cycle, x, y and $\eta *$ are assumed to be independent of external factors and a product-specific constant. The constant x describes the temperature difference between the ambient temperature and the temperature at the condenser. The constant y, however, can be perceived as the temperature difference between the internal compartment temperature and the temperature at the evaporator.

The energy consumption of a refrigerator (Rf) is calculated by integrating the overall power consumption over the respective requested period of time t_{total} (equation 4-15) assuming that the efficiency $\eta *$ is constant and independent of time and temperature:

$$Work_{t_{total}}^{Rf} = P_{off} \cdot t_{total} + \frac{1}{\eta *} \cdot \int_{0}^{t_{total}} \frac{\left[T_{out}(t) + x^{Rf}\right] - \left[T_{in}^{Rf}(t) - y^{Rf}\right]}{\left[T_{in}^{Rf}(t) - y^{Rf}\right]} \cdot \left\{\left[T_{out}(t) - T_{in}^{Rf}(t)\right] \cdot a + \frac{Q_{input}^{Rf}}{t_{total}}\right\} dt$$

(4-15)

where:

$Work_{t_{total}}^{Rf}$ = Energy consumed by a refrigerator during a period t_{total}

T_{in}^{Rf} = Target (adjusted) internal temperature of the refrigerator

Q_{input}^{Rf} = Additional heat load caused by placement of warm items into the refrigerator

The energy consumption of a freezer (Fr) is calculated analogously (equation 4-16):

$$Work^{Fr}_{t_{total}} = P_{off} \cdot t_{total} + \frac{1}{\eta *} \cdot \int_{0}^{t_{total}} \frac{\left[T_{out}(t) + x^{Fr}\right] - \left[T^{Fr}_{in}(t) - y^{Fr}\right]}{\left[T^{Fr}_{in}(t) - y^{Fr}\right]} \cdot \left\{\left[T_{out}(t) - T^{Fr}_{in}(t)\right] \cdot a + \frac{Q^{Fr}_{input}}{t_{total}}\right\} dt \tag{4-16}$$

where:

$Work^{Fr}_{t_{total}}$ = Energy consumed by a freezer during a period t_{total}

T^{Fr}_{in} = Target (adjusted) internal compartment temperature of the freezer

Q^{Fr}_{input} = Additional heat load caused by placement of warm items into the freezer

If a refrigerator-freezer combination (RFC) is concerned, the energy consumption is computed by combining equations 4-15 and 4-16:

$$\begin{aligned} Work^{RFC}_{t_{total}} = {} & P_{off} \cdot t_{total} + \alpha \cdot \frac{1}{\eta *} \cdot \int_{0}^{t_{total}} \frac{\left[T_{out}(t) + x^{Rf}\right] - \left[T^{Rf}_{in}(t) - y^{Rf}\right]}{\left[T^{Rf}_{in}(t) - y^{Rf}\right]} \cdot \left\{\left[T_{out}(t) - T^{Rf}_{in}(t)\right] \cdot a + \frac{Q^{Rf}_{input}}{t_{total}}\right\} dt \\ & + (1 - \alpha) \cdot \frac{1}{\eta *} \cdot \int_{0}^{t_{total}} \frac{\left[T_{out}(t) + x^{Fr}\right] - \left[T^{Fr}_{in}(t) - y^{Fr}\right]}{\left[T^{Fr}_{in}(t) - y^{Fr}\right]} \cdot \left\{\left[T_{out}(t) - T^{Fr}_{in}(t)\right] \cdot a + \frac{Q^{Fr}_{input}}{t_{total}}\right\} dt \end{aligned} \tag{4-17}$$

where $Work^{RFC}_{t_{total}}$ is the energy consumed by a refrigerator-freezer combination during a period t_{total} and α is a weighting factor.

In the case of a refrigerator-freezer combination, it is assumed that the efficiency factor $\eta *$ as well as the factor a are identically for the refrigerator and freezer compartment. The product-specific constants x, y, a, $\eta *$, α and P_{off} have to be determined experimentally.

The constant x is the difference between the average condenser and the ambient temperature, the constant y the difference between the average evaporator temperature and the average internal compartment temperature. So, both were derived respectively from the average condenser and evaporator temperature, which was measured under standard conditions defined in EN 15502:2005 by immersing a T-type thermocouple probe in the respective passage. Table 4-7 gives an overview of these constants, separately for each of the investigated appliances. The power consumption P_{off}, which is also shown in Table 4-7, was obtained by measuring the power consumed during the compressor off-cycle of each appliance.

Table 4-7: Overview of the product-specific constants *x*, *y*, a [source: BSH, 2010] and P_{off} [own source]

	Appliance 1	Appliance 2	Appliance 3	Appliance 4
x_{Rf}	19.6 K	25 K	19.2 K	19.6 K
y_{Rf}	8.3 K	33.7 K	37.1 K	30.6 K
x_{Fr}	-	15.9 K	19.2 K	-
y_{Fr}	-	16.6 K	14.1 K	-
a	1.424 W/K	1.8 W/K	1.695 W/K	0.789 W/K
P_{off}	1.5 W	1.2 W	0.5 / 6[4] W	0 W

The remaining factors α and η^* were derived from the experiments under static conditions by fitting the predicted and measured values using the method of least squares. In the present work, both factors were calculated by means of the Microsoft Excel add-in programme Solver.

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[4] The power consumption in compressor off-cycle is higher if the winter-switch is switched on

5 Results

At first, the findings of the empirical studies are presented in chapter 5.1 and 5.2, followed by the results of the laboratory experiments (5.3). The last subchapter (5.4) deals with the model validation.

5.1 Online survey

In the following, only selected results of the online survey are presented, which are of particular interest for the determination of test conditions for laboratory experiments.

5.1.1 Ambient temperatures

A total of 1011 participants were asked to estimate the maximum, minimum and normal temperature in the room, where their main refrigerator is placed.

The analysis of the answers shows that the average maximum ambient temperature was 24.5 °C (Figure 5-1). In the majority of investigated households (62.5 %), maximum values were within the range 20 °C to 31 °C. Temperature values of 32 °C or higher appear with a frequency of 15.2 %, values of 40 °C or higher with a frequency of 1.4 %. The results revealed statistically significant differences between Spain and the other three countries.

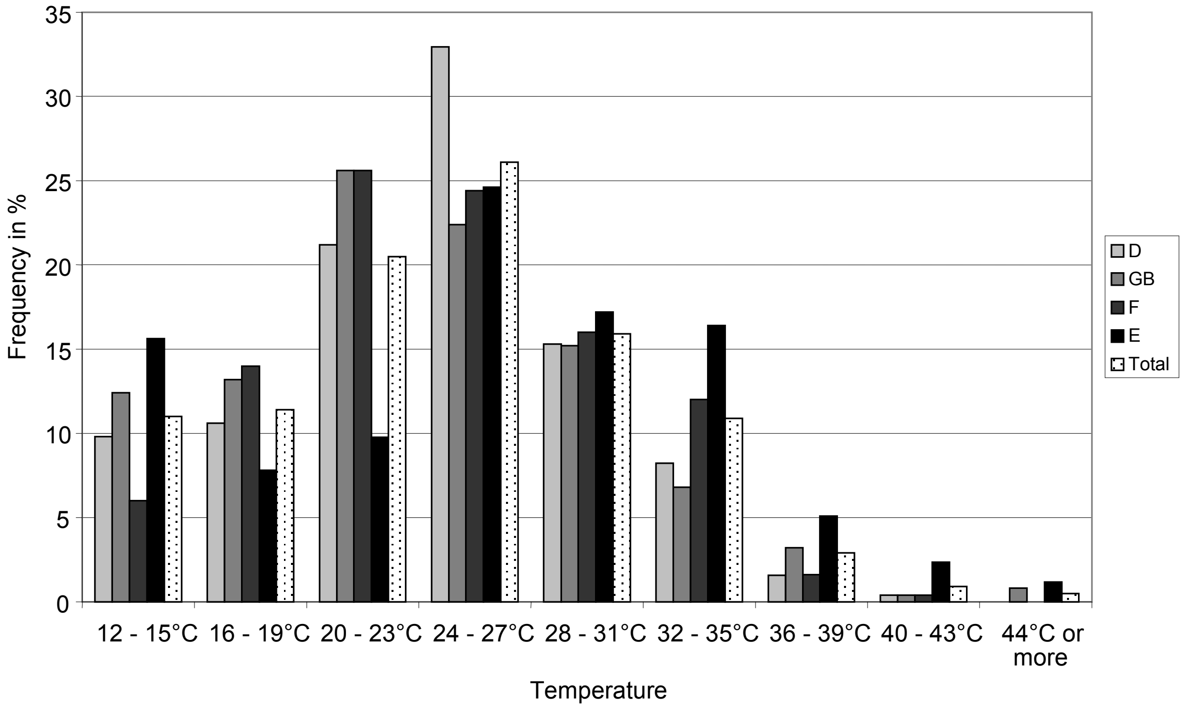

Figure 5-1: Maximum ambient temperature (n=1011)

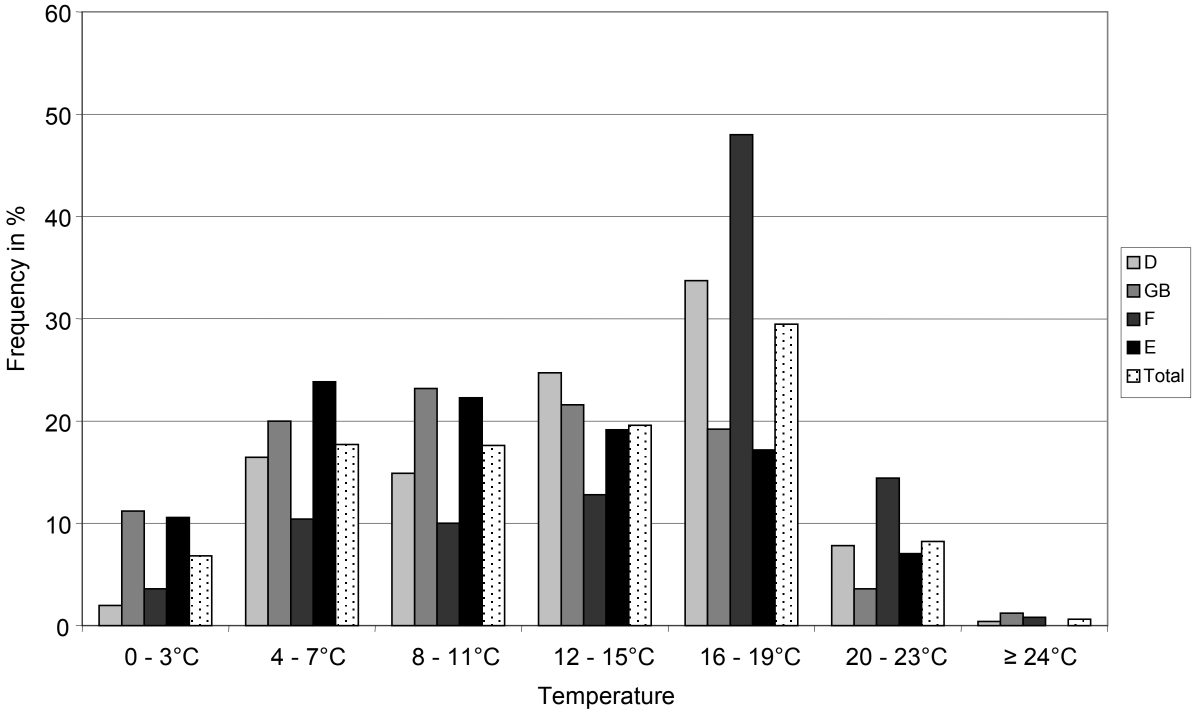

Figure 5-2: Minimum ambient temperature (n=1011)

Estimates of minimum temperature values range from 0 °C to 24 °C or higher with an overall mean of 12.5 °C (Figure 5-2). Almost half of all participants (49.1 %) state a minimum temperature within the range 12 °C to 19 °C. Minimum temperatures lower than 12 °C appears in 42.1 % of participating households, especially in Spain (56.6 %) and Great Britain (54.4 %). Both countries show statistically significant lower values than Germany and France ($p \leq 0.001$).

5.1.2 Internal temperature adjustment

The settings of refrigerator thermostats vary between different models and brands. A main distinction is between adjustment by numbered setting and the precise one by degree Celsius. All participants of the online study were asked about their actual temperature setting and which of the two possibilities of adjustment applied to them. Respondents indicating adjustment by numbered setting were additionally asked to state the number of possible adjustment steps. Due to a high number of missing answers, these data could not be analysed. In the following, only the results of participants with precise adjustment by degree Celsius (n=326) are presented (Figure 5-3).

Most of these respondents (66.3 %) choose a temperature setting within the range 3 °C and 6 °C whereas 4 °C is the most common adjustment. Temperatures below 3 °C are selected in 12.9 % of households and a total of 20.8 % choose a temperature between 7 °C and 12 °C. The average actual temperature setting is about 4.5 °C.

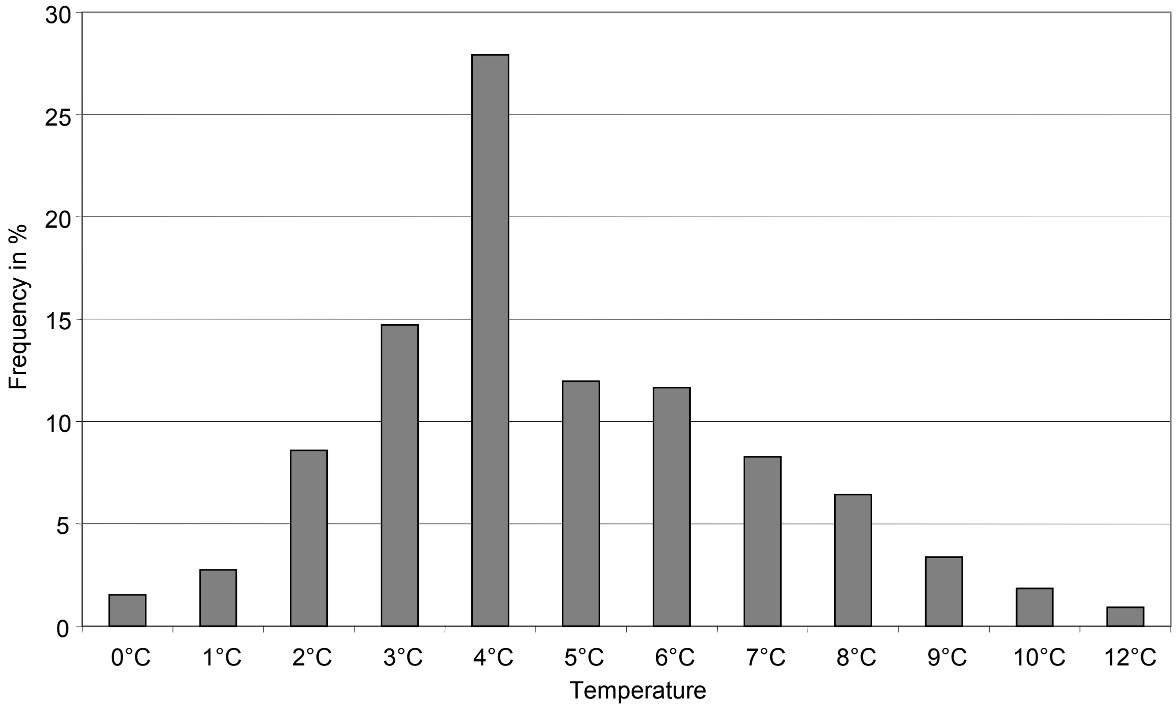

Figure 5-3: Compartment temperature adjustment (n=326)

5.1.3 Door openings

The participants were also asked to estimate the number of daily door openings of their main refrigerator. The distribution of the frequency of door openings per day is shown in Figure 5-4. The frequency ranges between 0 and over 40 times with an average number of 11. More than three third of respondents (78.3 %) state a frequency of up to 15 times per day. Considering the significance test, it can be concluded that smaller households open the door significantly less often than larger households. The differences between the countries' means, however, are statistically not significant except of the difference between Germany and Spain ($p \leq 0.05$), France and Spain ($p \leq 0.001$) and Great Britain and Spain ($p \leq 0.05$).

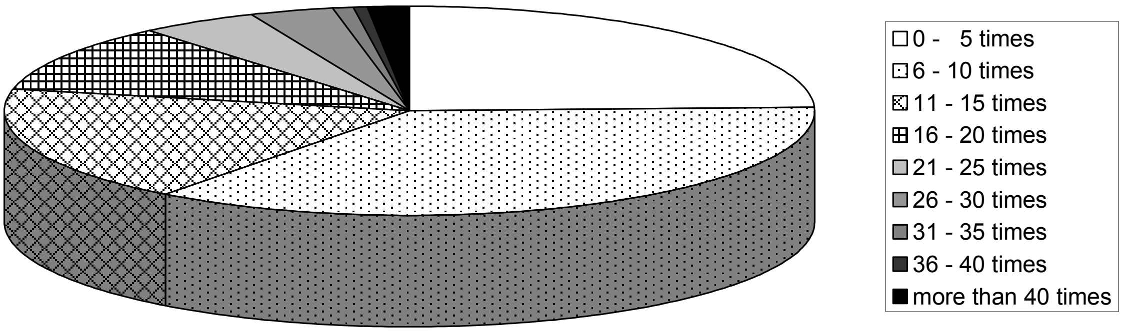

Figure 5-4: Frequency of door openings per day

5.1.4 Estimated use of refrigerator’s capacity

The degree of capacity use mainly depends on the household size. Especially young single households tend to use small amounts of refrigerator’s capacity. If all participants are considered, refrigerators are mostly rated as sometimes completely and sometimes less full (49.9 %). Approximately 40 % describe their refrigerator as, at most, half full. Regarding the differences between the four countries, the consumers of the British and Spanish sample state a significantly lower degree of filling than the participants in Germany and France (Figure 5-5).

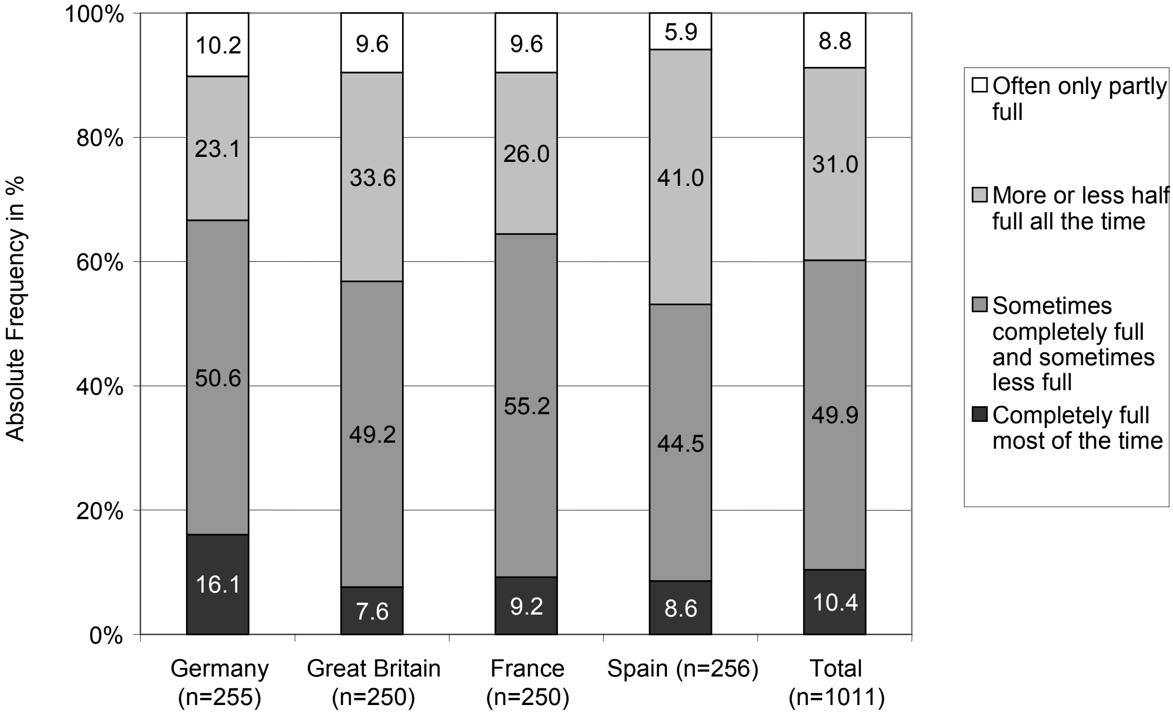

Figure 5-5: Degree of use of refrigerator’s capacity (Respondents’ assessment)

5.1.5 Placement of hot food

When asked about their food storage practices, most of the participants stated to always cool down hot food before putting it into the refrigerator (71.6 %). Whereas the differences between Germany, Great Britain and Spain are just marginal and statistically not significant, the storage behaviour of the French respondents differs significantly from that of the other respondents ($p \leq 0.001$). The results of this question are presented in Figure 5-6.

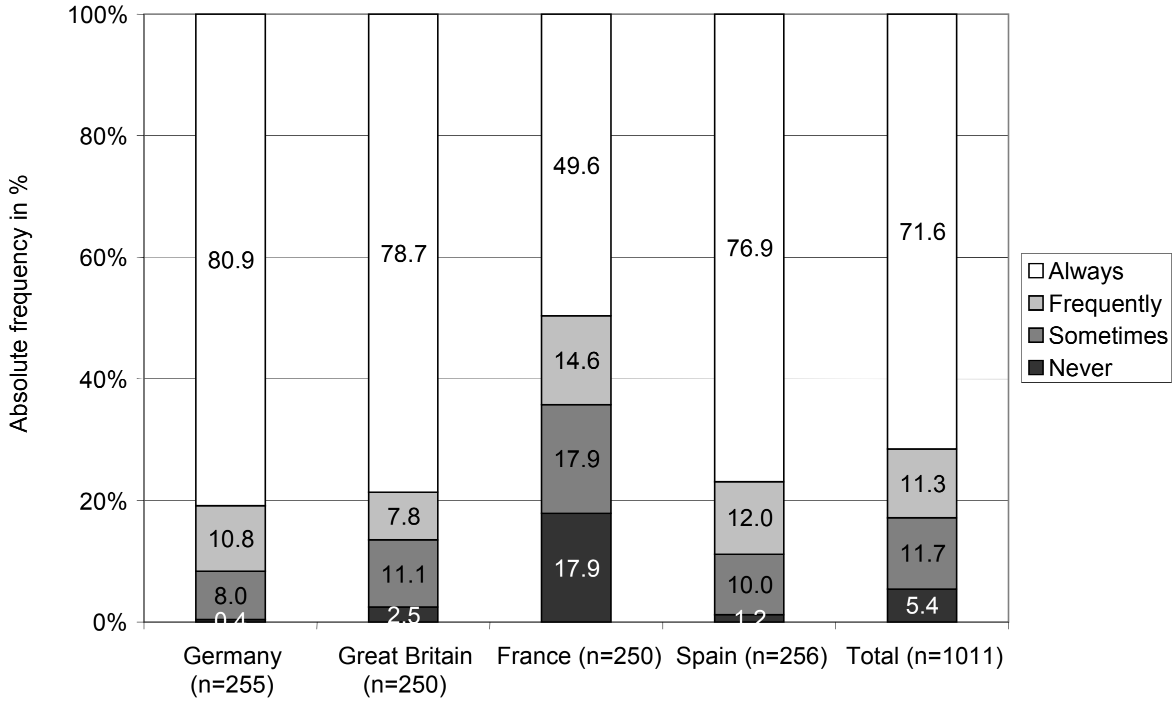

Figure 5-6: Cooling down of hot food before placing it into the refrigerator

5.2 In-home study

Whereas the online study aimed to gain a first insight into the conditions in private homes and the usage behaviour of domestic refrigerators, the in-home study is an in-depth-study. It was carried out in order to obtain detailed knowledge about all processes related with food refrigeration in private households.

During the observation period, the internal compartment temperatures of participants' refrigerators were recorded every minute. Moreover, the participating households took notes of the quantity of food placed into and removed from the refrigerator by means of two different diaries. Additionally, they took pictures of the inside of their refrigerator in order to assess the use of capacity and to analyse loading patterns.

5.2.1 Compartment temperatures

The internal compartment temperature on the middle shelf was recorded every minute over a period of eleven days. A total of 82 temperature files were exploitable. Based on the values recorded every minute, the arithmetic mean of the internal temperature of each participating household was calculated. A Box plot analysis of the arithmetic means is shown in Figure 5-7. It can be seen that the differences between the households are considerable. Average internal compartment temperatures range from 0 °C up to over 12 °C where the highest values occur in France. The median values are within the range 4.4 °C and 6.4 °C. The highest average mean temperature is found in France (6.7 °C) followed by Germany (6.2 °C) and Great Britain (5.2 °C). Spain shows an average mean temperature of 4.1 °C. The differences between the countries are statistically significant ($p \leq 0.05$) except for the differences between Germany and France, Great Britain and France and Great Britain and Spain.

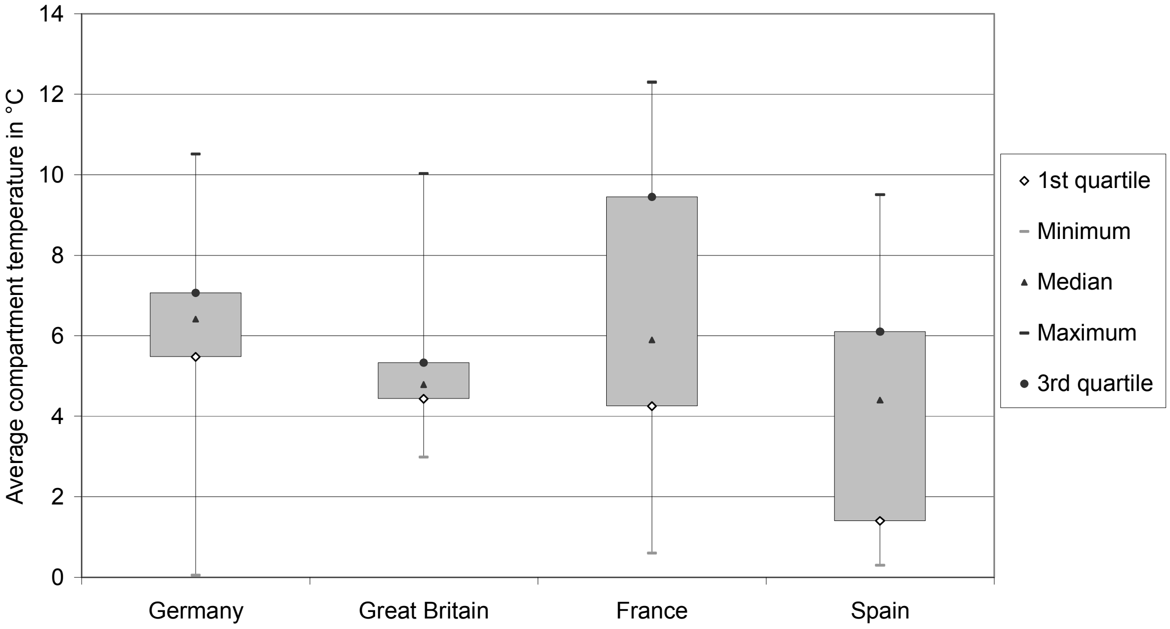

Figure 5-7: Distribution of average internal compartment temperature

5.2.2 Food shopping behaviour

By means of diaries, the food shopping behaviour of the respondents was recorded. Besides the type and quantity of chilled food purchased during the test period, the participants' notes also allow to calculate the food shopping frequency.

Regarding the average food shopping frequency per week, the differences between the four countries are just marginal and statistically not significant. The frequency ranges from 0.5 to 8 times per week with a median between 4 and 4.4. At least half of all respondents purchase chilled food between 3 and 6 times per week (Figure 5-8). Comparing the different types of households, there is a noticeable trend concerning the food shopping frequency with increased household size (Figure 5-9). Whereas participants of young single households indicate significant lower shopping frequencies than respondents of multi-person households and elder single households, the differences between all other households are statistically not significant.

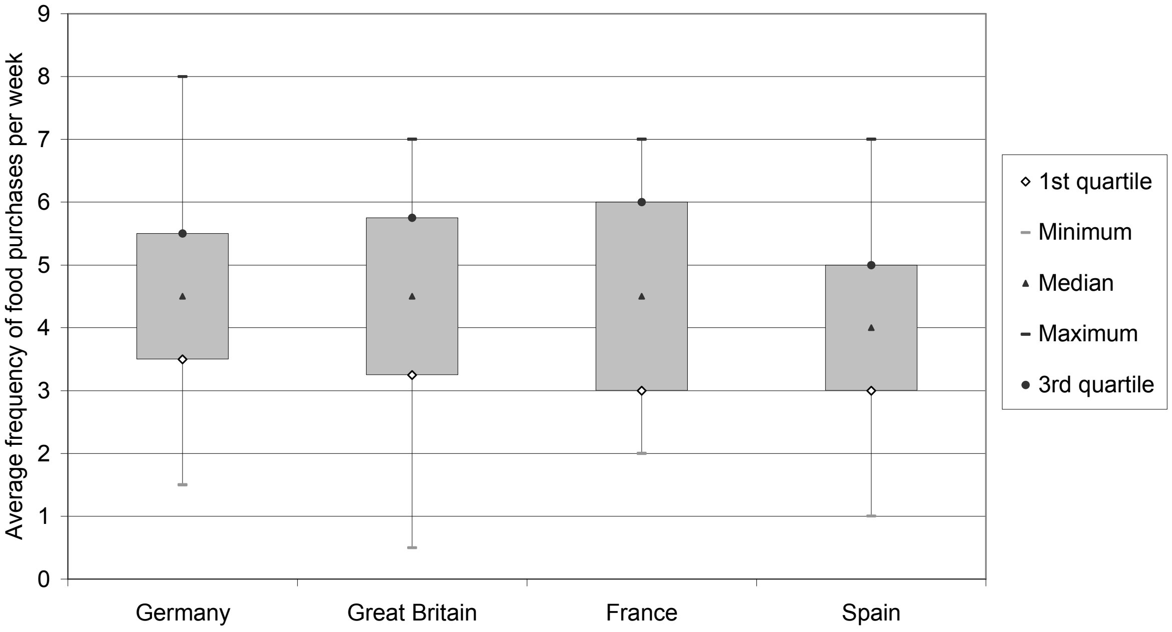

Figure 5-8: Average food shopping frequency per week (comparison between countries)

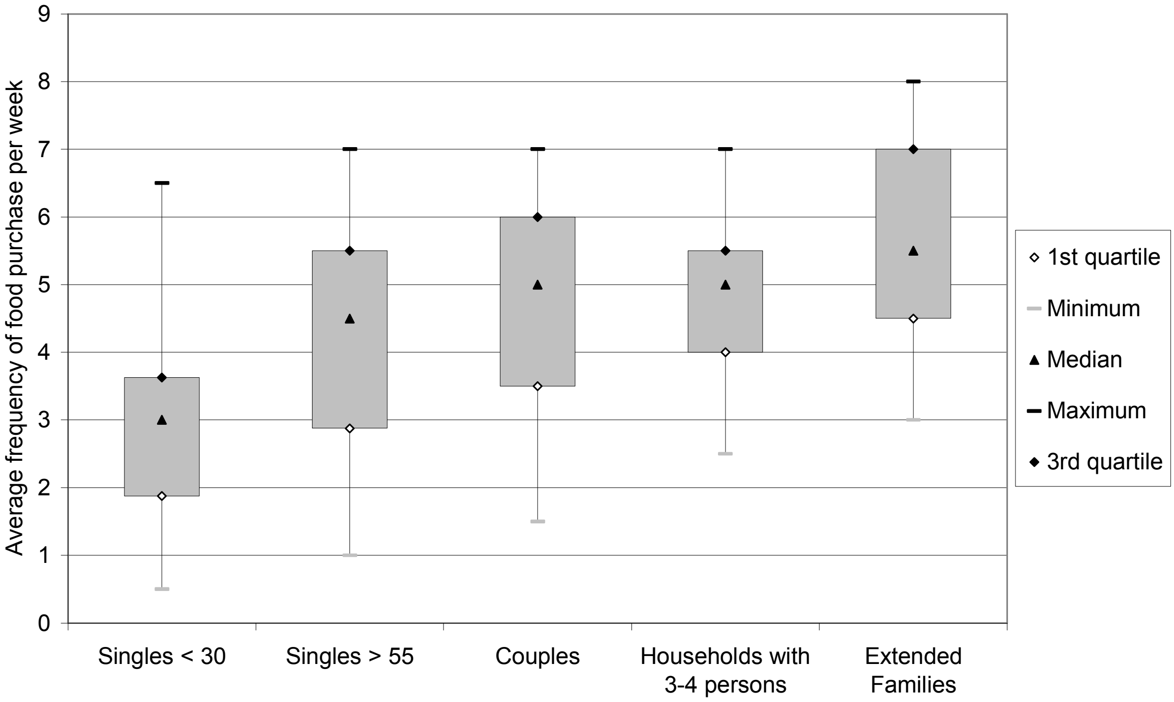

Figure 5-9: Average food shopping frequency per week (comparison between types of households)

Regarding the amount of foodstuffs placed into the refrigerator after food shopping, the median values of all four countries are broadly in the same range. Average quantities of at most 5.7 kg are stored after purchase in more than three-third of all participating households (Figure 5-10). The differences between the households, however, are found to be enormous. Especially in Spain, the average amount of foodstuffs placed into the refrigerator ranges from 0.4 kg up to 14.4 kg.

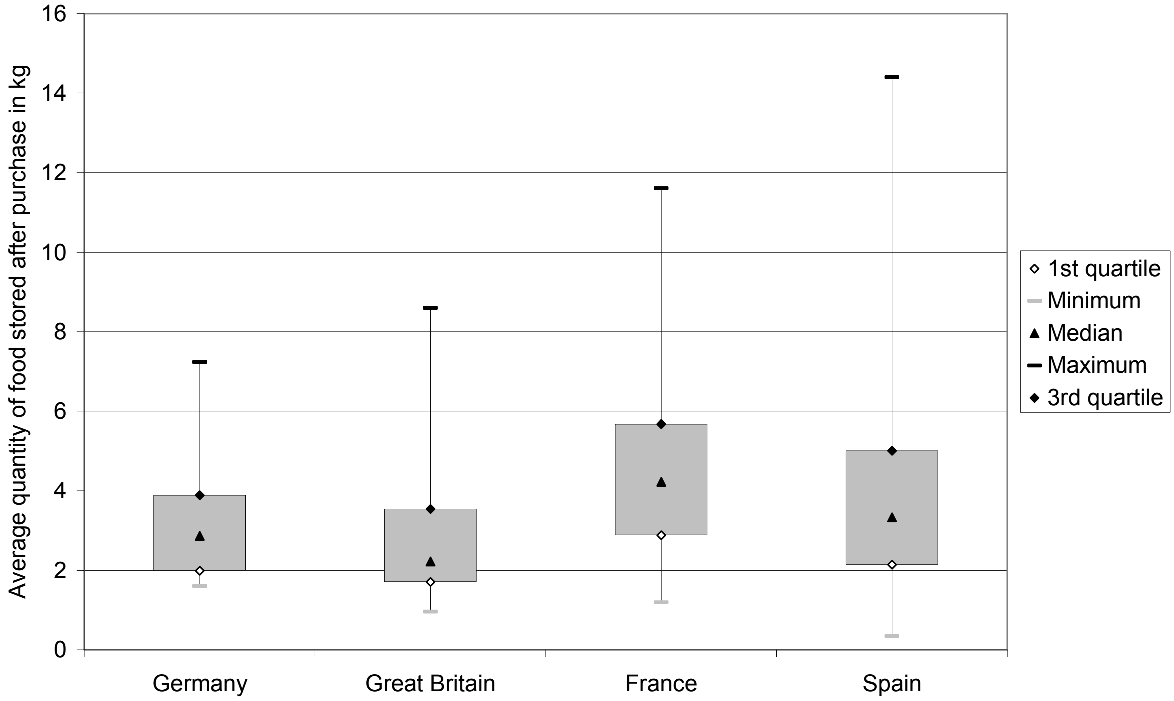

Figure 5-10: Average quantity of food placed into the refrigerator after shopping (comparison between countries)

A comparison of different kind of households (Figure 5-11) also shows a slight tendency towards a rise in stored amounts with increasing household sizes. Statistically significant differences occur between single households and extended families ($p \leq 0.05$) and households with 3-4 persons and extended families ($p \leq 0.05$).

Regarding the indicated single values (Figure 5-12), amounts between 0.02 and 28.2 kg are stored after purchase. Small amounts up to 3 kg are placed into the refrigerator with a frequency of around 60 %. 30 % of the values are within the range 3 and 10 kg. Nearly 10 % of the values are higher than 10 kg, whereas quantities of more than 16 kg appear with a frequency of 1 %.

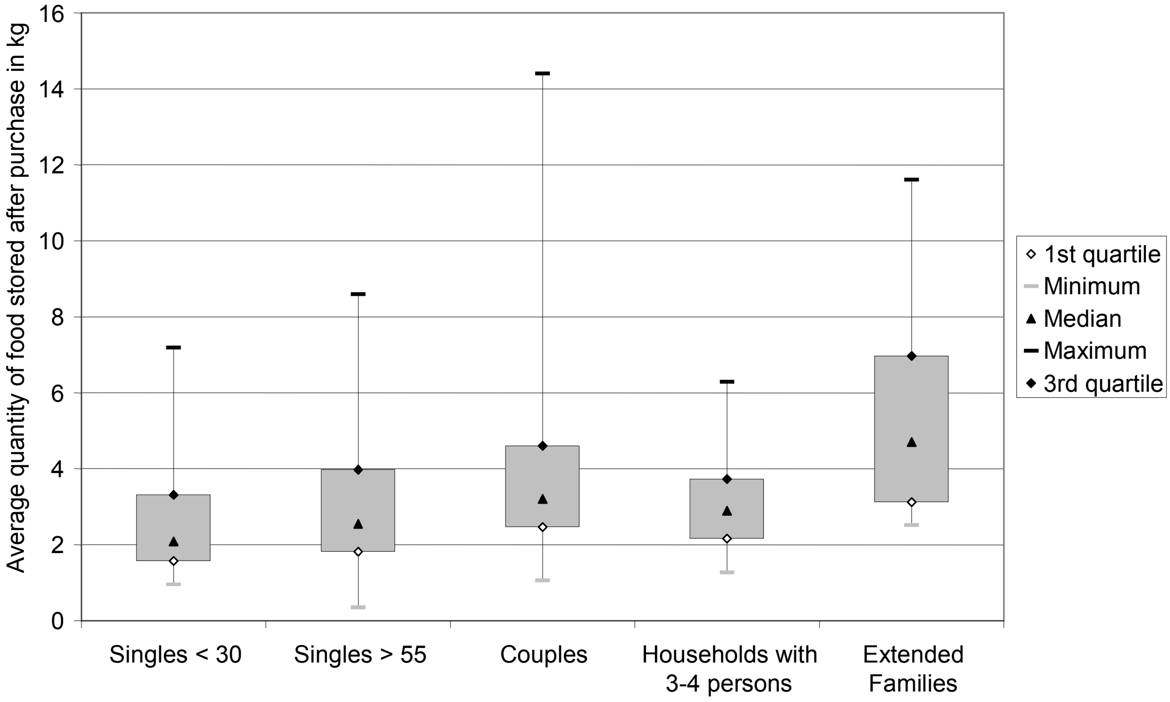

Figure 5-11: Average quantity of food placed into the refrigerator after shopping (comparison between types of households)

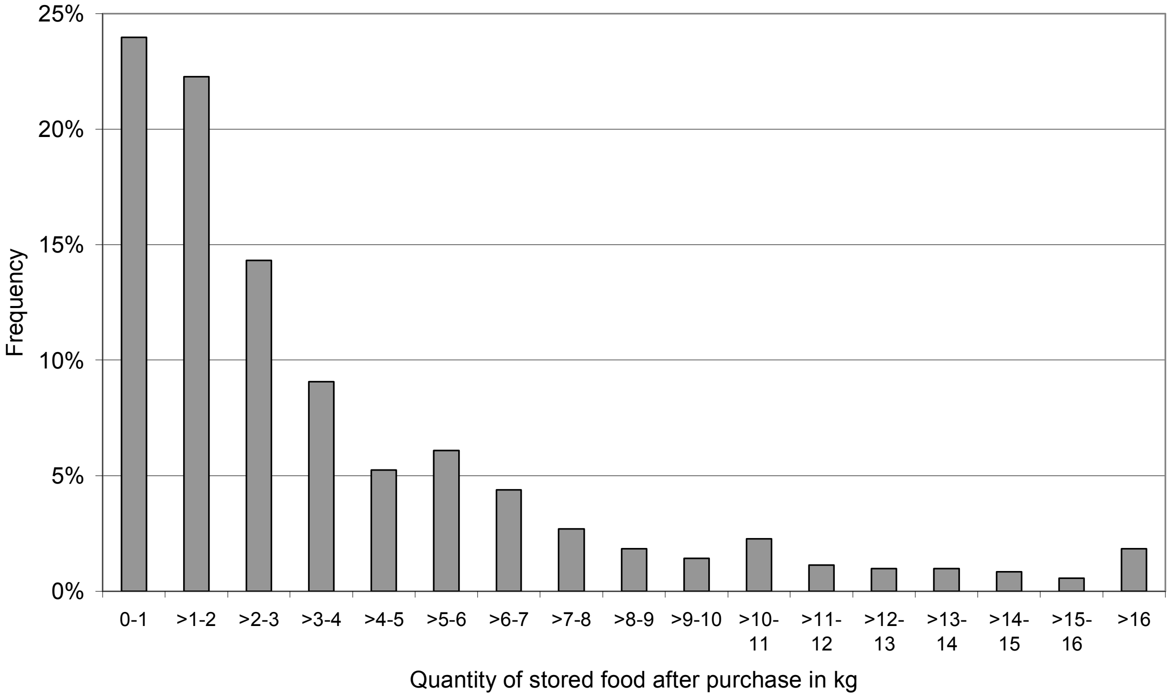

Figure 5-12: Frequency distribution of quantities of food stored after purchase based on single values

Based on the quantities of food stored after purchase, the amount of additional heat load was calculated as described in chapter 4.2. Figure 5-13 shows the 95 % percentiles of the computed values depending on the respective country-specific scenario. All calculated 95 % percentiles are within the range 355 kJ and 979 kJ. The amount of heat increases with rising ambient temperature and with rising time lapses between the retail store and the domestic refrigerator. The computed 95 % percentiles range between 355 kJ and 495 kJ for the German sample and between 642 kJ and 723 kJ for the British sample. For participating French households, values between 601 kJ and 866 kJ are calculated. The 95 % percentiles in Spain are within the range 730 kJ and 979 kJ.

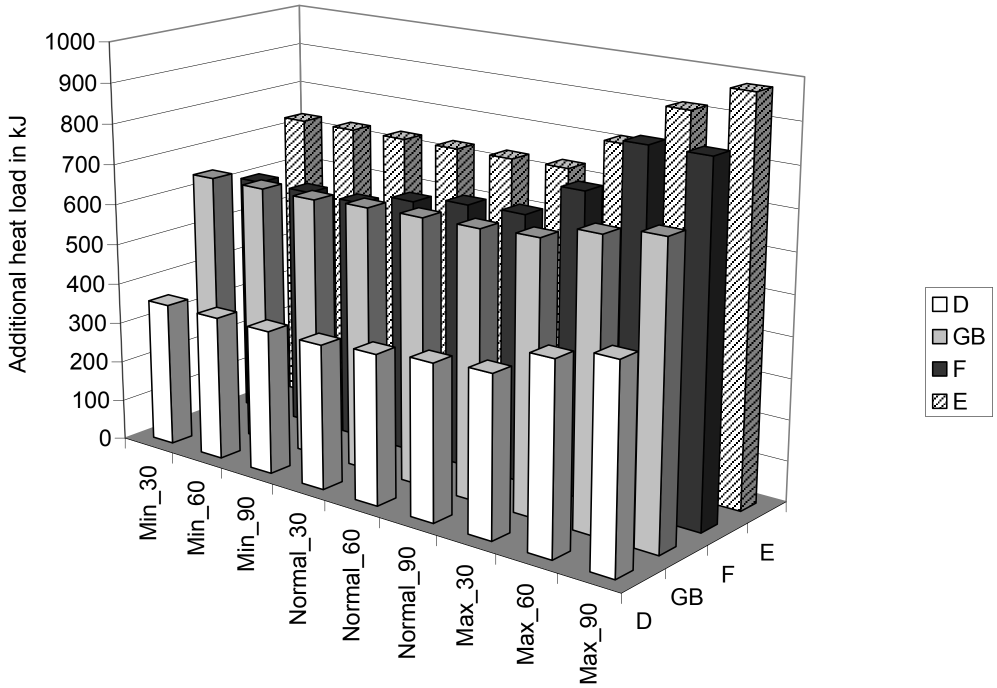

Figure 5-13: Additional heat load caused by placement of foodstuffs after purchase (95 % percentile)

5.2.3 Observed use of refrigerator's capacity

After the field phase, all refrigerators were assessed by means of the pictures towards the degree of capacity of refrigerators net volume used.

The assessment shows that most of appliances are moderately filled (Figure 5-14). With the exception of extended families, less than 30 % of participating households fill their refrigerator to its full extent. Regarding extended families, full capacity is used in about half of all observed households. The proportion of refrigerators, whose volume is only slightly filled, is relatively high in young and elder single households (9.6 % and 8.7 %, respectively). Generally speaking, the degree of filling increases with rising household sizes.

Comparing the use of refrigerators' capacity of different countries, the proportion of fully filled appliances is the highest in Germany. The highest share of slightly filled refrigerators is found in French households.

Regarding the net volume of the refrigerators, it was observed that larger appliances are more likely to be fully filled than smaller ones.

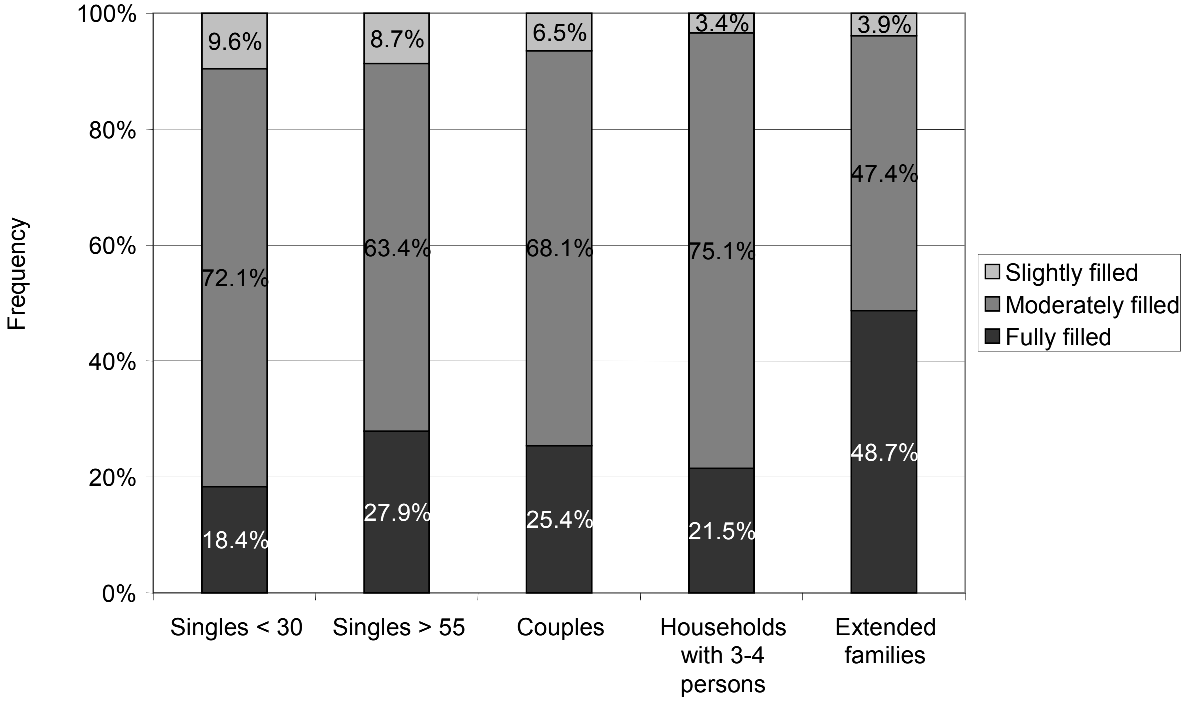

Figure 5-14: Observed use of refrigerators' capacity

Beyond that, a more detailed calculation of the degree of space used for food storage was carried out. It shows that at the most 23-28 % of net volume is used, even of appliances assessed as fully filled.

5.3 Laboratory experiments

In this section, the experimental designs used and the measured energy consumptions as the investigated response are presented. The effect of each factor on the response is described. Additionally, this section demonstrates the results in terms of the ANOVA and the validation of the regression models developed. Box-Behnken experimental designs that allow the estimation of full quadratic models including interaction effects were used to investigate the influence of different factors on the refrigerators' energy consumption. All in all, three different experimental series were carried out.

5.3.1 Experimental series under static conditions

In this experimental series, the influence of ambient temperature, internal compartment temperature and capacity use on refrigerators' energy consumption was investigated. The results of the laboratory trials performed according to the experimental design are presented in Table 5-1 for all appliances.

These results were input for further analysis (cf. Chapter 4.3.3).

By means of the Design Expert software, a quadratic model as the highest order polynomial where the model is not aliased and the additional terms are significant was fitted to each response. Insignificant model terms were step-wise eliminated.

Table 5-2 summarizes ANOVA results for the significant model terms (marked in bold) and hierarchical terms that are insignificant by themselves but are part of significant higher order terms. The coefficients of determination R^2, Adjusted R^2 and Predicted R^2 and the Adequate Precision are also presented in this table.

Table 5-1: Results of experiments under static conditions

Run	**Factor A** Ambient temperature in K	**Factor B** Compartment temperature setting in K/ numbered setting	**Factor C** Load in % of net volume	**Response** Energy consumption in Wh			
				Appliance 1	**Appliance 2**	**Appliance 3**	**Appliance 4**
1	295.5	279/ 278[1]/ 3[2]	12.5	366.1	691.6	762.0	205.9
2	278.0	279/ 278[1]/ 3[2]	25.0	31.9	177.6	138.5	0.0
3	295.5	275/ 275[1]/ 5[2]	25.0	409.8	753.7	1111.0	279.6
4	295.5	283/ 281[1]/ 1[2]	25.0	258.6	595.3	579.4	207.2
5	295.5	279/ 278[1]/ 3[2]	12.5	364.2	698.8	753.3	215.2
6	295.5	283/ 281[1]/ 1[2]	0.0	285.1	580.5	567.0	188.7
7	278.0	275/ 275[1]/ 5[2]	12.5	60.9	221.6	394.6	0.0
8	313.0	279/ 278[1]/ 3[2]	25.0	848.8	2013.5	2445.0	539.0
9	313.0	283/ 281[1]/ 1[2]	12.5	765.8	1686.4	2135.2	404.6
10	295.5	275/ 275[1]/ 5[2]	0.0	425.6	812.0	958.6	270.4
11	278.0	279/ 278[1]/ 3[2]	0.0	31.6	183.4	271.2	0.0
12	295.5	279/ 278[1]/ 3[2]	12.5	366.0	688.5	744.9	219.6
13	313.0	275/ 275[1]/ 5[2]	12.5	954.2	2092.8	2422.6	975.1
14	313.0	279/ 278[1]/ 3[2]	0.0	888.1	1986.7	2392.3	526.0
15	278.0	283/ 281[1]/ 1[2]	12.5	28.4	178.4	146.1	0.0
16	295.5	279/ 278[1]/ 3[2]	12.5	362.7	686.6	768.7	203.4
17	295.5	279/ 278[1]/ 3[2]	12.5	367.9	675.4	736.0	219.0

[1] Temperature setting of appliance 3
[2] Temperature setting of appliance 4

The Prob > F values for all quadratic models (appliance 1 to 4) are lower than 0.0001, which confirms the significance of the models. The goodness of fit of the four models is additionally demonstrated by high R^2 values of at least 0.9931. In all cases, the Predicted R^2 is in reasonable agreement with the Adjusted R^2. Adequate Precision ratios well above 4 indicate adequate model discrimination. Except for appliance 3, the Lack of Fit was found to be insignificant.

Table 5-2: Overview of ANOVA table for energy consumption measured under static conditions, reduced quadratic model

	Appliance 1	**Appliance 2**	**Appliance 3**	**Appliance 4**
Source	**Prob > F**	**Prob > F**	**Prob > F**	**Prob > F**
Model	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
A	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
B	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
C	0.4376			0.2189
AB	**< 0.0001**	**0.0004**		**< 0.0001**
AC				
BC	**0.0039**			
A^2	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.0002**
B^2				**0.0078**
C^2	**0.0019**			
Lack of Fit	0.0513	0.0534	**0.0011**	0.1567
R^2	0.9999	0.9994	0.9931	0.9975
Adj R^2	0.9998	0.9991	0.9916	0.9959
Pred R^2	0.9990	0.9978	0.9865	0.9852
Adeq Precision	350.049	187.148	68.924	76.010

The results of the ANOVA for the models show that the main effect of the ambient temperature (A) and the internal compartment temperature setting (B) as well as the quadratic effect of the ambient temperature (A^2) are overall significant model terms. The two-factor interaction of the ambient temperature and the internal compartment temperature setting (AB) are significant terms in three of four models. The two-factor interaction of the internal compartment temperature setting and the load (BC) and the second-order effect of the internal compartment temperature setting (B^2) and the load (C^2), respectively, were found to be significant in one case.

The final models are shown in terms of coded factors (Equation 5-1 to 5-4) that allow identifying the relative significance of each factor by comparing the factor coefficients.

It is clear from all four equations, that the main and the quadratic effect of the ambient temperature (A and A^2) have the biggest influence on refrigerators' energy consumption. The main effect of the internal compartment temperature setting (B) is also of particular importance. However, it is a negative effect. That means that a reduction in internal temperature increases the energy consumption of the refrigerator and vice versa. The main effect of the load (C) is found to be of relatively minor importance.

Appliance 1 (5-1)

$$\begin{aligned}\text{Energy consumption (Wh)} = &+366.37\\ &+407.99 * A\\ &-57.55 * B\\ &+1.39 * C\\ &-38.98 * A * B\\ &+10.37 * B * C\\ &+84.71 * A^2\\ &+9.79 * C^2\end{aligned}$$

Appliance 2 (5-2)

$$\begin{aligned}\text{Energy consumption (Wh)} = &+686.93\\ &+904.93 * A\\ &-97.48 * B\\ &-75.87 * A * B\\ &+408.24 * A^2\end{aligned}$$

Appliance 3 (5-3)

$$\begin{aligned}\text{Energy consumption (Wh)} = &+775.66\\ &+1055.59 * A\\ &-182.39 * B\\ &+517.53 * A^2\end{aligned}$$

Appliance 4 (5-4)

$$\begin{aligned}\text{Energy consumption (Wh)} = &+214.48\\ &+258.73 * A\\ &+43.72 * B\\ &+5.09 * C\\ &+48.92 * A * B\\ &+34.42 * A^2\\ &+19.68 * C^2\end{aligned}$$

The interaction graphs of the respective appliances illustrated in Figure 5-15 examine the interaction effects of the factors ambient temperature (A) and temperature setting (B) on refrigerators energy consumption. With the exception of graph 3, the graphs indicate that a reduction in internal temperature setting has a greater impact on energy consumption at higher ambient temperatures than at lower ones.

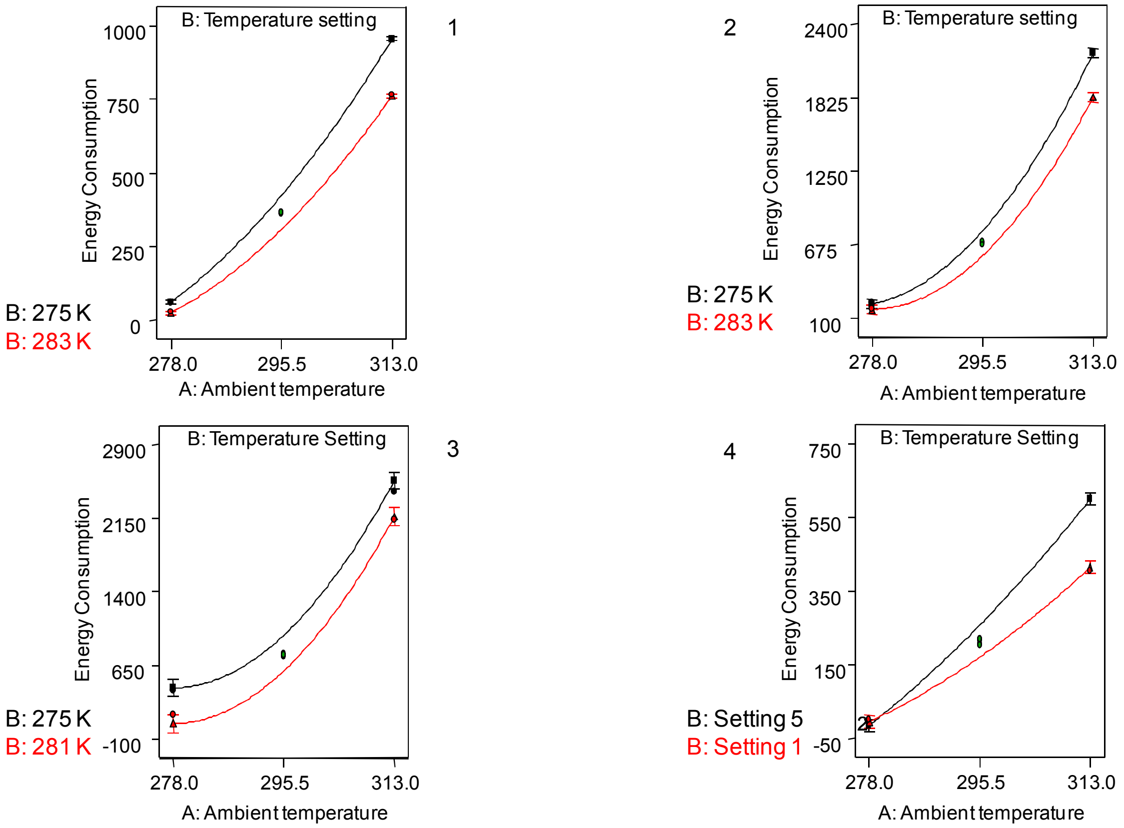

Figure 5-15: Interaction effects of ambient temperature (A) and temperature setting (B) on energy consumption under static conditions

The 3D surface graphs for energy consumption under static conditions are illustrated in Figure 5-16 for all investigated appliances. In accordance to the quadratic model fitted, all of them show a curvilinear profile. The graphs highlight the interaction between the ambient temperature and the internal temperature setting. An increase in ambient temperature induces a considerable increase of refrigerators' energy consumption while a reduction of internal temperature setting additionally fosters this process. The difference between the ambient temperature and the internal temperature setting (ΔT) and the energy consumption are found to act in a proportional manner. The energy consumption rises with increasing temperature difference.

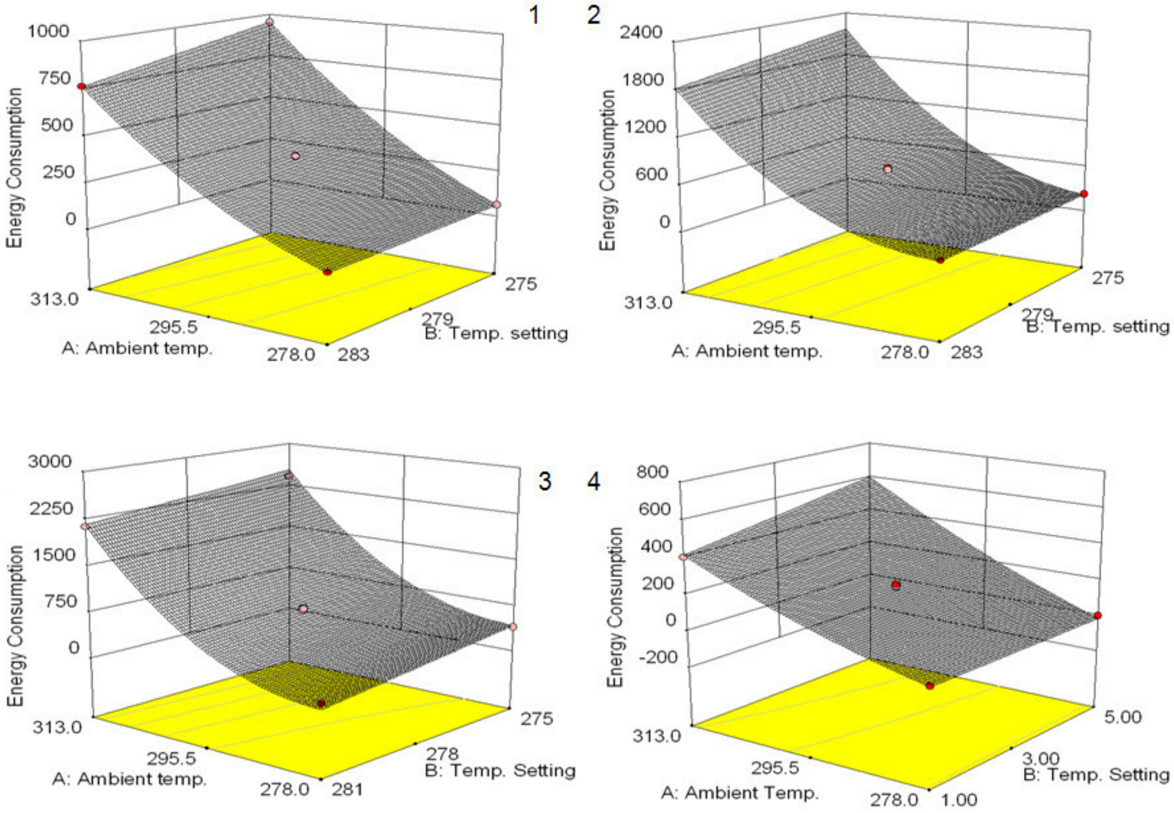

Figure 5-16: 3D surfaces of refrigerators' energy consumption under static conditions

Figure 5-17 shows perturbation plots that help to compare the effect of all the factors at a particular point in the design space. From these plots it can be assumed once again that the refrigerators' energy consumption is highly sensitive to the ambient temperature (A), which is represented by steep curvilinear effect. It is evident that the internal compartment temperature setting (B) has a slightly negative effect. An increase in compartment temperature setting results in a decrease of energy consumed. The non significance of the parameter load (C) is also demonstrated. There is almost no effect of varying the amount of load within the ranges 0 % to 25 % of appliances' net volume.

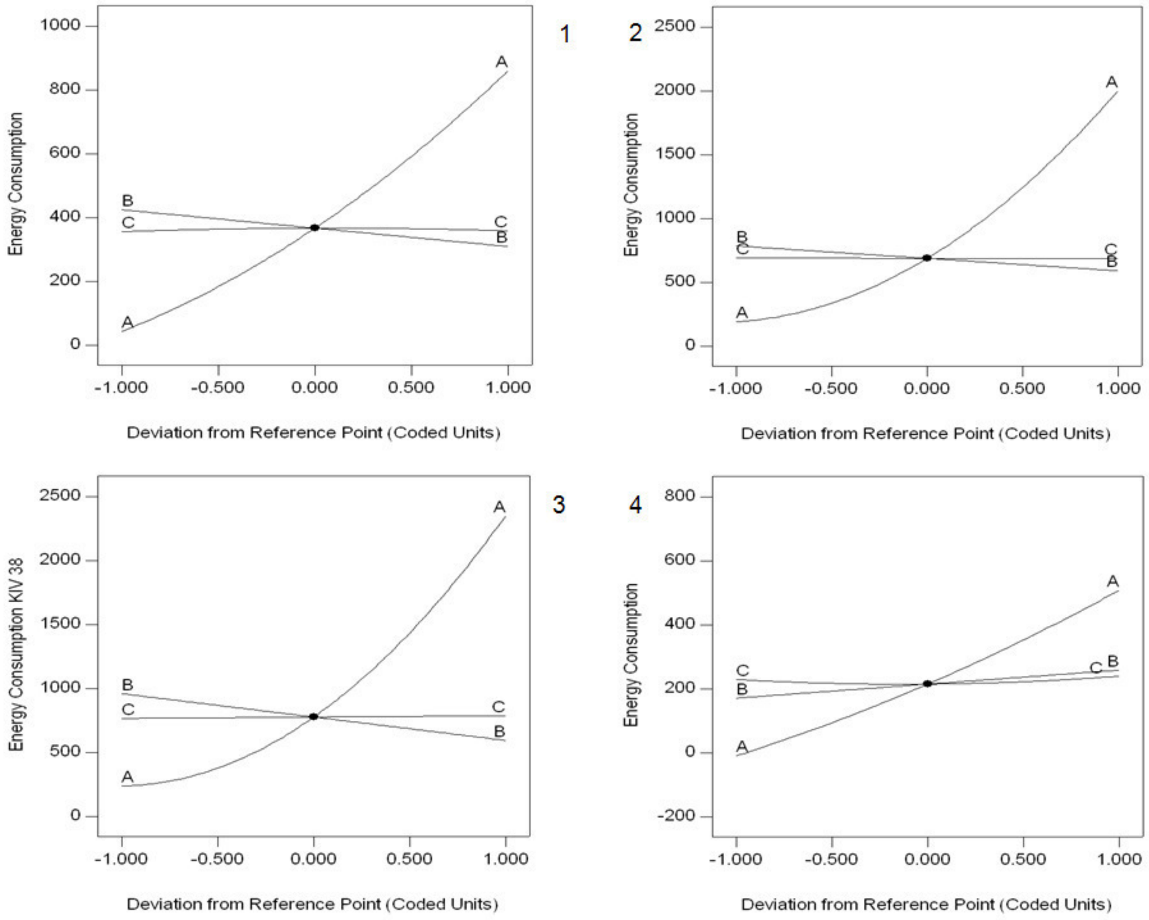

Figure 5-17: Perturbation plot showing the effect of all parameters on refrigerators' energy consumption under static conditions

5.3.2 Experimental series under diurnal ambient conditions

In this experimental series, the impact of diurnally varying ambient temperatures and the internal compartment temperature was investigated. Table 5-3 provides an overview of the experiments and the corresponding measured energy consumptions.

As a result of analysing the measured energy consumptions, a quadratic model as the highest order polynomial where the model is not aliased and the additional terms are significant was fitted to each response. The step-wise regression method led to the elimination of insignificant model terms.

Table 5-3: Results of experiments under diurnal ambient conditions

Run	**Factor A** Ambient temperature in K	**Factor B** Variation in ambient temperature in K	**Factor C** Compartment temperature setting in K	**Response** Energy consumption in Wh			
				Appliance 1 load 0 %	**Appliance 1 load 12.5 %**	**Appliance 2 load 0 %**	**Appliance 2 load 12.5 %**
1	295.5	17.5	279	741.2	711.7	1576.4	1567.4
2	278.0	35.0	279	560.2	554.2	1252.8	1269.3
3	295.5	17.5	275	779.2	794.1	1711.3	1685.9
4	295.5	0.0	275	429.5	484.1	765.9	863.1
5	295.5	17.5	279	714.5	696.7	1597.6	1563.8
6	295.5	0.0	283	285.1	314.3	582.2	645.7
7	278.0	17.5	275	350.7	324.3	645.1	647.0
8	278.0	0.0	279	31.6	30.8	183.5	189.2
9	295.5	17.5	283	685.1	604.7	1410.6	1366.4
10	313.0	0.0	275	878.3	956.2	2083.3	2094.4
11	278.0	35.0	283	460.5	467.7	1130.2	1114.0
12	295.5	17.5	279	709.0	714.7	1598.5	1575.8
13	313.0	0.0	283	796.3	765.8	1832.6	1744.7
14	313.0	0.0	279	889.6	878.3	1988.0	2096.9
15	278.0	17.5	283	208.1	134.3	476.1	398.8

ANOVA results for the significant model terms (marked in bold) are summarized in Table **5-4**, which also presents other adequacy measures like the coefficients of determination R^2, Adjusted R^2 and Predicted R^2 and the Adequate Precision.

Table 5-4: ANOVA table for energy consumption under diurnal ambient conditions, reduced quadratic polynomial model

	Appliance 1 load: 0 %	**Appliance 1 load: 12.5 %**	**Appliance 2 load: 0 %**	**Appliance 2 load: 12.5 %**
Source	**Prob > F**	**Prob > F**	**Prob > F**	**Prob > F**
Model	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
A	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
B	**0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
C	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
AB			**0.0070**	
AC	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
BC			**0.0158**	
A^2	**< 0.0001**	**0.0003**	**< 0.0001**	**< 0.0001**
B^2				
C^2	**0.0002**	**< 0.0001**	**0.00012**	**0.0004**
Lack of Fit	0.3183	0.6450	0.2939	**0.0235**
R^2	0.9932	0.9994	0.9996	0.9981
Adj R^2	0.9881	0.9989	0.9991	0.9964
Pred R^2	N/A	N/A	N/A	N/A
Adeq Precision	40.966	152.234	129.560	78.299

All Prob > F values are lower than 0.0001, which indicates that all models are significant. Adequate Precision ratios well above 4 indicate adequate model discrimination. The coefficients of determination are close to 1, which confirms the goodness of fit. The Lack of Fit was found to be insignificant except for appliance 2 with 12.5 % load.

The results of the ANOVA for the reduced quadratic models show that the main effects of the ambient temperature (A), the internal compartment temperature setting (B) and the temperature variation (C) as well as the quadratic effect of A and C and the two-factor interaction of A and B are overall significant model terms. The two-factor interaction of the ambient temperature and the internal compartment temperature setting (AB) and of the internal compartment temperature setting and the temperature variation (BC) were found to be significant in one case.

Equation 5-5 to 5-8 present the final mathematical models in terms of coded factors. These equations allow identifying the relative significance of each factor by comparing the factor coefficients.

All four equations indicate that the ambient temperature (A) (main and quadratic effect) is the most significant factor whereas the main and quadratic effect of the temperature variation (C) has a lesser significance on the refrigerators' energy consumption. While the negative effect of the internal compartment temperature setting (B) is of minor importance, the two-factor interaction of the ambient temperature and the temperature variation (AC) has a greater level of importance.

Appliance 1
load: 0 % (5-5)

$$
\begin{aligned}
\text{Energy consumption (Wh)} = &+725.80 \\
&+674.47 * A \\
&-60.35 * B \\
&+517.36 * C \\
&+405.10 * A * C \\
&+228.07 * A^2 \\
&+148.86 * C^2
\end{aligned}
$$

Appliance 1
load: 12.5 % (5-6)

$$
\begin{aligned}
\text{Energy consumption (Wh)} = &+704.38 \\
&+524.66 * A \\
&-92.10 * B \\
&369.78 * C \\
&+106.68 * A * C \\
&49.58 * A^2 \\
&64.60 * C^2
\end{aligned}
$$

Appliance 2
load: 0 % (5-7)

$$
\begin{aligned}
\text{Energy consumption (Wh)} = &+1578.88 \\
&+1430.74 * A \\
&-146.57 * B \\
&+1065.40 * C \\
&-64.33 * A * B \\
&+527.73 * A * C \\
&-52.45 * B * C \\
&+412.46 * A^2 \\
&+160.57 * C^2
\end{aligned}
$$

Appliance 2
load 12.5 % (5-8)

$$
\begin{aligned}
\text{Energy consumption (Wh)} = &+1551.86 \\
&+1328.93 * A \\
&-142.64 * B \\
&+1000.65 * C \\
&+463.76 * A * C \\
&+299.97 * A^2 \\
&+203.19 * C^2
\end{aligned}
$$

The 3D surface graphs illustrated in Figure 5-18 show the energy consumption of refrigerators under diurnal ambient conditions as a function of the ambient temperature and the temperature variation. All of them show a curvilinear profile in accordance to the quadratic model fitted. The graphs demonstrate that both the ambient temperature and the temperature variation exert a significant effect on the refrigerators' energy consumption. An increase of the ambient temperature (A) without changing the temperature variation (C) leads to an increase of energy consumption. The energy consumption also increases with growing temperature variation. The higher the ambient temperature and the temperature variation, the higher is also the energy consumption. Due to the experiments performed in this experimental series, only the black-shaded surface area can be used for interpretation.

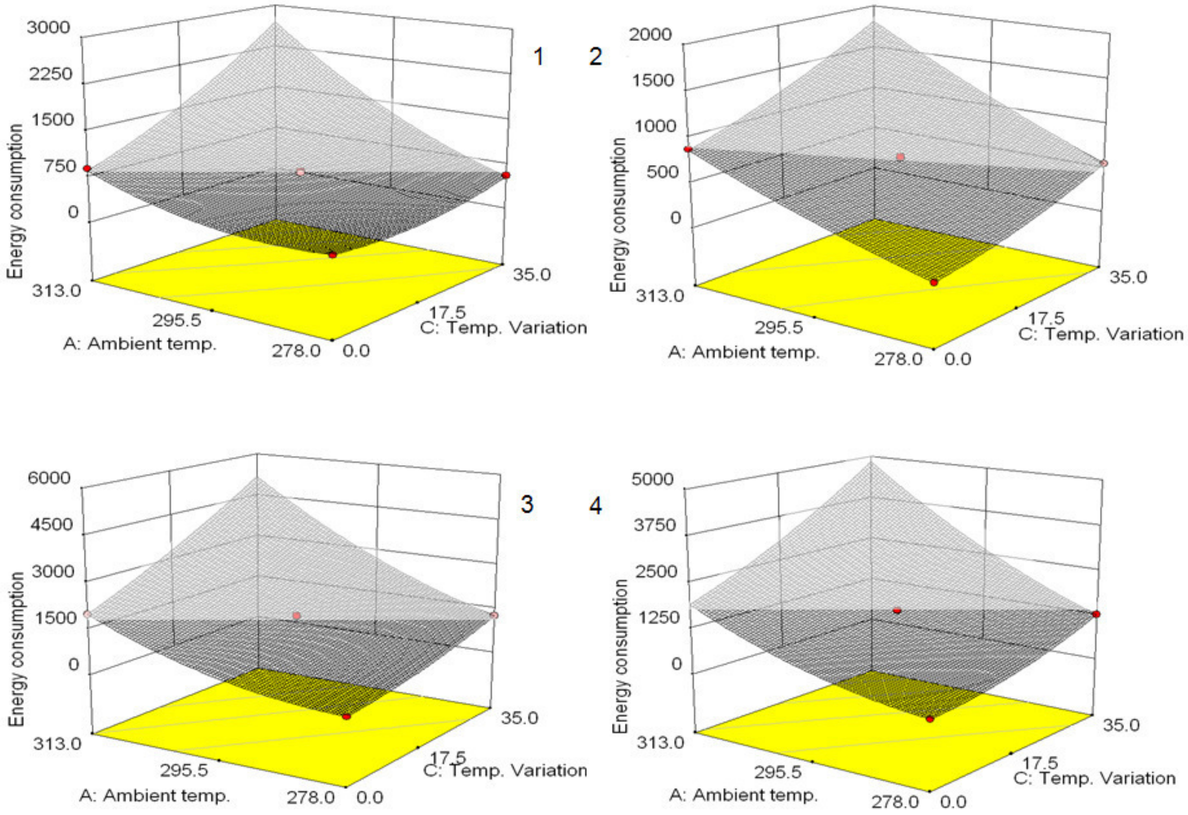

Figure 5-18: 3D surfaces of refrigerators' energy consumption under diurnal ambient conditions

5.3.3 Experimental series under dynamic conditions

In this experimental series, the influence of ambient temperature, internal compartment temperature and additional heat load on refrigerators' energy consumption was investigated. The results of the laboratory experiments are shown in Table 5-5. The results presented were used for further analysis (cf. Chapter 4.3.3).

Table 5-5: Results of experiments under dynamic conditions

Run	**Factor A** Ambient temperature in K	**Factor B** Compartment temperature setting in K/ numbered setting	**Factor C** Additional heat load in kJ	**Response** Energy consumption in Wh			
				Appliance 1	**Appliance 2**	**Appliance 3**	**Appliance 4**
1	295.5	279/ 278[1]/ 3[2]	650	396.0	866.2	1032.5	268.4
2	278.0	279/ 278[1]/ 3[2]	1000	121.1	420.1	540.9	138.0
3	295.5	275/ 275[1]/ 5[2]	1000	597.6	1137.5	1872.2	460.6
4	295.5	283/ 281[1]/ 1[2]	1000	453.1	1008.2	1169.4	253.1
5	295.5	279/ 278[1]/ 3[2]	650	458.9	839.9	1124.7	278.5
6	295.5	283/ 281[1]/ 1[2]	300	36.4	748.8	925.4	229.9
7	278.0	275/ 275[1]/ 5[2]	650	195.1	344.0	524.3	131.2
8	313.0	279/ 278[1]/ 3[2]	1000	1092.0	2393.5	2487.4	710.6
9	313.0	283/ 281[1]/ 1[2]	650	898.5	2311.0	2481.8	471.6
10	295.5	275/ 275[1]/ 5[2]	300	531.9	944.1	1367.6	347.0
11	278.0	279/ 278[1]/ 3[2]	300	31.7	216.3	245.4	54.9
12	295.5	279/ 278[1]/ 3[2]	650	478.5	851.1	1092.5	290.1
13	313.0	275/ 275[1]/ 5[2]	650	1156.9	2497.0	2445.2	1026.5
14	313.0	279/ 278[1]/ 3[2]	300	975.6	2218.3	2451.7	614.4
15	278.0	283/ 281[1]/ 1[2]	650	28.9	255.1	138.5	100.9

[1] Temperature setting of appliance 3
[2] Temperature setting of appliance 4

A quadratic model was fitted to each response. It is the highest order polynomial where the model is not aliased and the additional terms are significant. Insignificant model terms were eliminated using the step-wise regression method.

Table 5-6 summarizes ANOVA results for the significant model terms (marked in bold). The coefficients of determination R^2, Adjusted R^2 and Predicted R^2 and the Adequate Precision are also presented in this table.

Table 5-6: Overview of ANOVA table for energy consumption measured under static conditions, reduced quadratic model

	Appliance 1	**Appliance 2**	**Appliance 3**	**Appliance 4**
Source	**Prob > F**	**Prob > F**	**Prob > F**	**Prob > F**
Model	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
A	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
B	**< 0.0001**	**0.0017**	**0.0117**	**< 0.0001**
C	**0.0046**	**< 0.0001**	0.0505	**0.0257**
AB				**0.0002**
AC				
BC				
A^2	**0.0004**	**< 0.0001**	0.0605	**0.0011**
B^2		**0.0105**		0.0506
C^2		**0.0375**		
Lack of Fit	0.7603	0.1145	0.0580	0.0520
R^2	0.9934	0.9990	0.9696	0.9862
Adj R^2	0.9908	0.9981	0.9574	0.9758
Pred R^2	0.9865	0.9946	0.9285	0.9149
Adeq Precision	55.192	97.418	24.982	33.408

The Prob > F values for all quadratic models (appliance 1 to 4) are lower than 0.0001, which confirms the significance of the models. Adequate Precision ratios of at least 24.982 show that an adequate model discrimination has been achieved for all four models. The Lack of Fit is found to be insignificant in all four cases. High R^2 values close to 1 confirm the goodness of fit of the models. In all cases, the Predicted R^2 is in reasonable agreement with the Adjusted R^2.

The results of the ANOVA for the reduced quadratic models show that the main effects of the ambient temperature (A), the internal compartment temperature setting (B) and the additional heat load (C) as well as the quadratic effect of the ambient temperature (A^2) are significant model terms. The second-order effect of the internal compartment temperature setting (B^2) and the load (C^2), respectively, were found to be significant in one case.

The final models in terms of coded factors are presented below (Equation 5-9 to 5-12). By comparing the factor coefficients of these equations, the relative significance of each factor is identified.

Appliance 1

$$\begin{aligned}\text{Energy consumption (Wh)} = &+468.49\\ &+468.28 * A\\ &-92.20 * B\\ &+45.15 * C\\ &+93.99 * A^2\end{aligned} \tag{5-9}$$

Appliance 2

$$\begin{aligned}\text{Energy consumption (Wh)} = &+852.40\\ &+1011.23 * A\\ &-63.13 * B\\ &+103.98 * C\\ &+414.08 * A^2\\ &+61.68 * B^2\\ &+45.58 * C^2\end{aligned} \tag{5-10}$$

Appliance 3

$$\begin{aligned}\text{Energy consumption (Wh)} = &+1226.33\\ &+1052.13 * A\\ &-186.78 * B\\ &+134.98 * C\\ &+188.07 * A^2\end{aligned} \tag{5-11}$$

Appliance 4

$$\begin{aligned}\text{Energy consumption (Wh)} = &+276.10\\ &+299.76 * A\\ &+113.73 * B\\ &+39.51 * C\\ &+131.15 * A * B\\ &+105.55 * A^2\\ &+48.73 * B^2\end{aligned} \tag{5-12}$$

It is clear from these equations that the ambient temperature (A) (main and quadratic effect) has the highest impact on refrigerators' energy consumption. The internal compartment temperature setting (B) as well as the additional heat load (C) also influences the energy consumption. Their impact, however, is markedly lower than the impact of the ambient temperature.

Figure 5-19 (1 to 4) illustrates the 3D surface graphs that examine the effects of the two significant factors ambient temperature (A) and additional heat load (C) on refrigerators' energy consumption. The graph demonstrates once again that both factors exert a significant effect on the response. The steep curvature in the factor ambient temperature shows that the response is highly sensitive to this factor. It is evident that there is little or no interaction effect between the factors A and C.

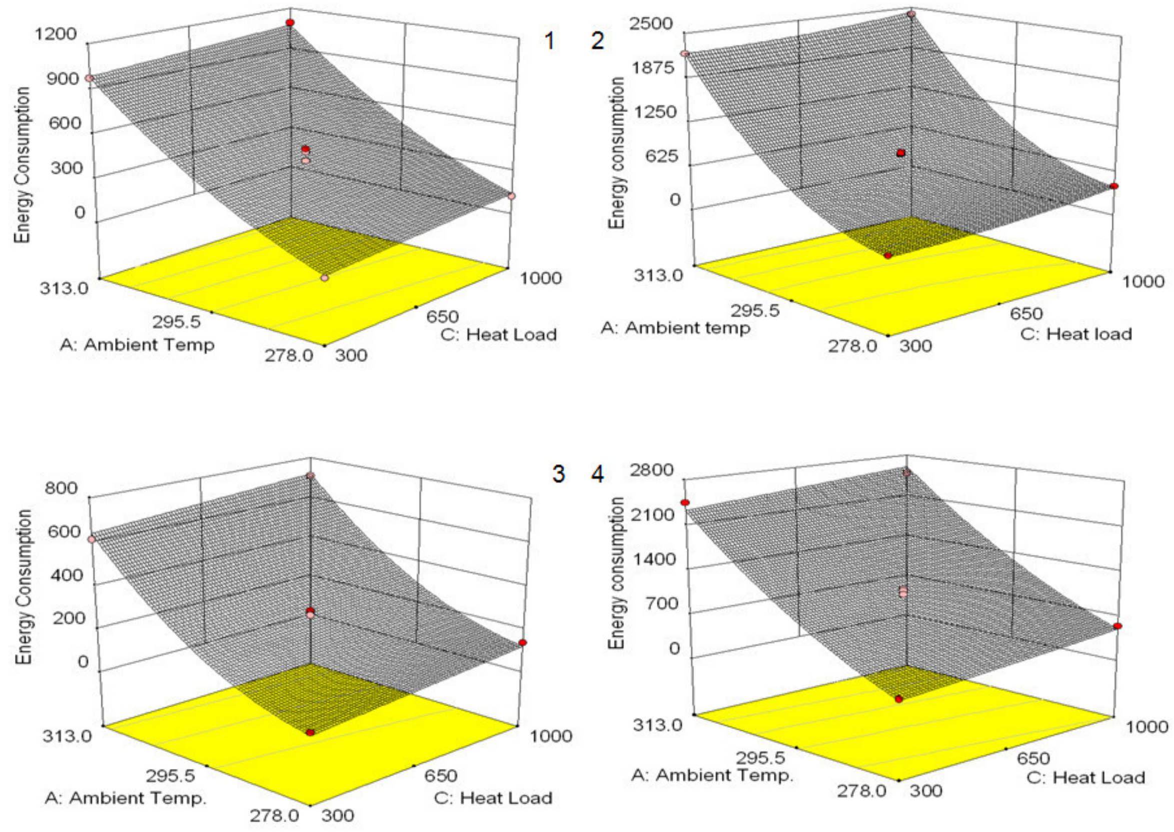

Figure 5-19: 3D surfaces of refrigerators' energy consumption under dynamic conditions

5.3.4 Experiments concerning the effect of door openings

Additional experiments were carried out in order to investigate the effect of door openings on refrigerators' energy consumption at two different ambient temperatures (295.5 K and 313 K, respectively). The door was opened 36 times within 24 hours for each 15 seconds, which corresponds to the average conditions in European households. Figure 5-20 and Figure 5-21 show summarizing comparisons between the energy consumption of appliances operating under static conditions and the energy consumption of appliances exposed to a regime of door openings. The ambient temperature as well as the internal compartment temperature setting and the load are identical in each case. Figure 5-20 highlights the results of appliance 1 at an ambient temperature of 295.5 K (left site) and of 313.0 K (right site). Figure 5-21 illustrates the results of appliance 2 in the same order.

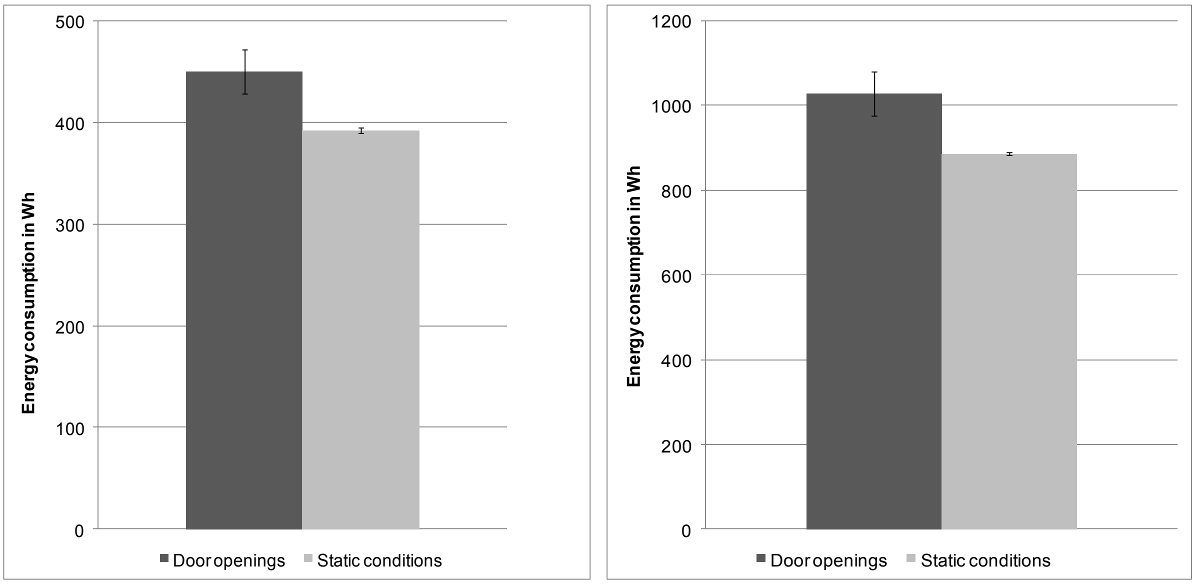

Figure 5-20: Energy consumption of refrigerators with and without door openings at an ambient temperature of 295.5 K (left site) and 313.0 K (right site), appliance 1

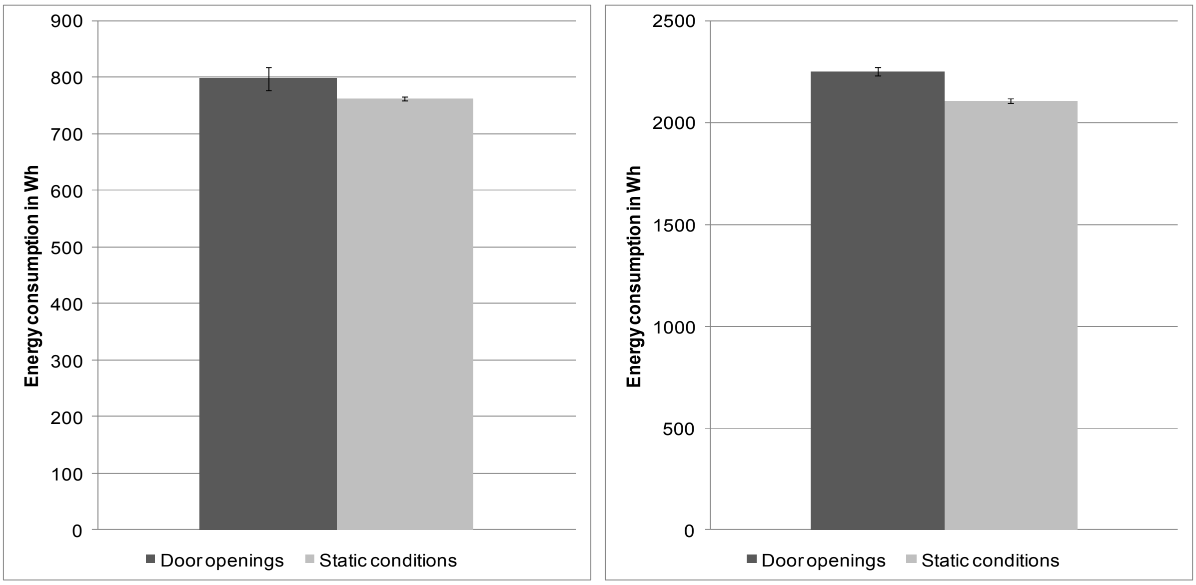

Figure 5-21: Energy consumption of refrigerators with and without door openings at an ambient temperature of 295.5 K (left site) and 313.0 K (right site), appliance 2

In all four cases, the refrigerator consumed more energy when it is exposed to a number of door openings. An additional energy consumption of 0.16 Wh and 0.41 Wh per litre net volume was found for appliance 1 at an ambient temperature of 295.5 K and 313.0 K, respectively. The energy consumption of appliance 2 rises by approximately 0.12 Wh per litre net volume at an ambient temperature of 295.5 K and by 0.51 Wh per litre net volume at an ambient temperature of 313.0 K.

In terms of a single opening process, the consumption per litre net volume of appliance 1 increases by 0.005 to 0.011 Wh. The additional consumption per door opening of appliance 2 is about 0.003 to 0.014 Wh per litre net volume.

5.4 Results of the model validation

The developed model was validated by comparing the energy consumption model predictions with its experimental counterparts, separately for each of the experimental series. In order to enable a direct comparison between the measured and the predicted values, energy consumption was calculated for a period of 24 hours.

In a first step, the required input variables for modelling were derived from the experiments under static conditions as described in Chapter 4.4. Table 5-7 summarizes these input variables for all investigated appliances.

Table 5-7: Input variables for modelling derived from experiments under static conditions

	Appliance 1	Appliance 2	Appliance 3	Appliance 4
η^*	0.327	0.349	0.290	0.382
P_{off}	1.5 W	1.2 W	0.5/ 6[5] W	0 W
α	-	0.87	0.92	-

For the purpose of calculating the energy consumption under diurnal ambient conditions, the actual measured ambient temperatures of each experiment in K, which were recorded every minute, were supplied as input variables (T_{out}). Due to the recording interval, the model equations (equation 4-15 and 4-17, respectively) were slightly modified and the energy consumption under diurnal ambient conditions was

---

[5] If the ambient temperature is lower than 16 °C, the power consumed during the compressor off-cycle (P_{off}) of appliance 3 is 6 W instead of 0.5 W due to the automatic winter-switch

not calculated by integration but by summing up the computed energy consumptions of every minute over a period of 24 hours. As described in chapter 4.4, the adjusted target temperatures in K (internal compartment temperature setting) were used as further input data (T_{in}).

In this way, the expectable energy consumptions were calculated and were compared to the measured data. Figure 5-22 and Figure 5-23 display the comparison between measured and predicted values under diurnal ambient conditions for appliance 1 and 2, respectively. By means of the different symbols, the results of experiments were optically differentiated according to the amount of load (0 % of net volume and 12.5 % of net volume). The dotted line through the origin shows the expected values if the measured and predicted data totally comply with each other.

It can be seen that a consistent agreement was achieved for both appliances. Most of the values randomly scatter around the ideal dotted line. In regard to appliance 1, the energy consumption in the upper range is slightly overestimated by the model (Figure 5-22). In view of appliance 2, the highest deviations appear in the range between 500 and 1000 Wh (Figure 5-23).

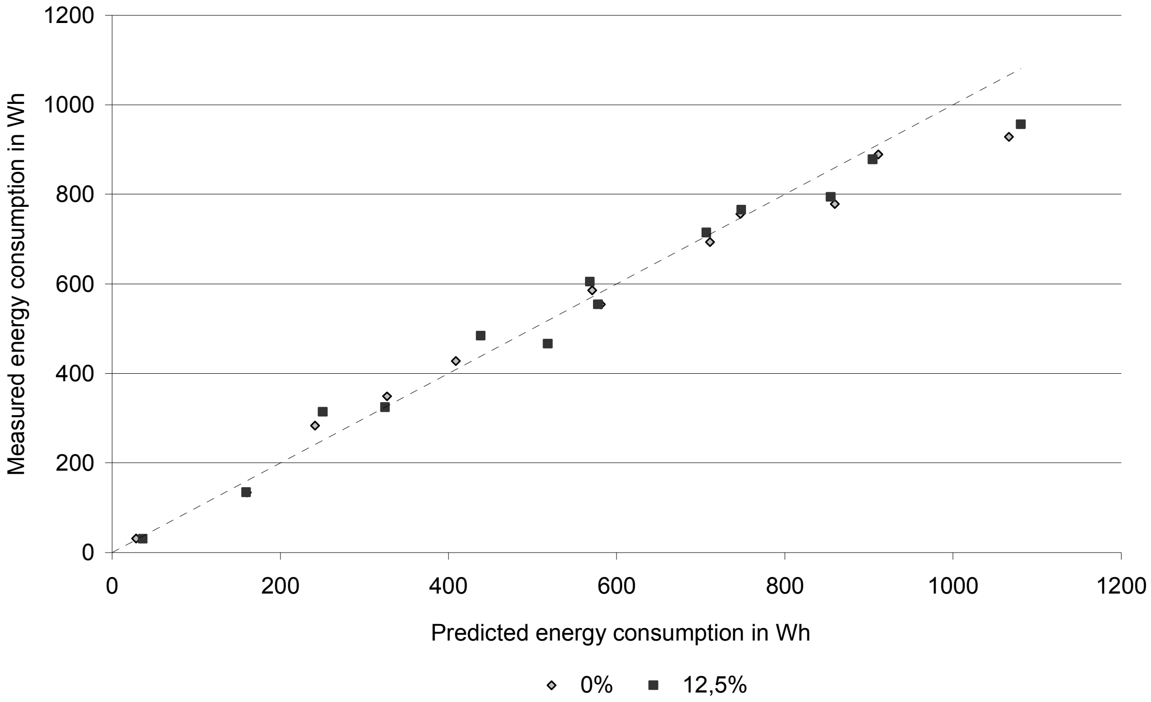

Figure 5-22: Comparison between measured and predicted energy consumption per 24 h under diurnal ambient conditions, appliance 1, load: 0 % and 12.5 % of net volume (the dotted line through the origin shows the expected values if the measured and predicted data totally comply with each other)

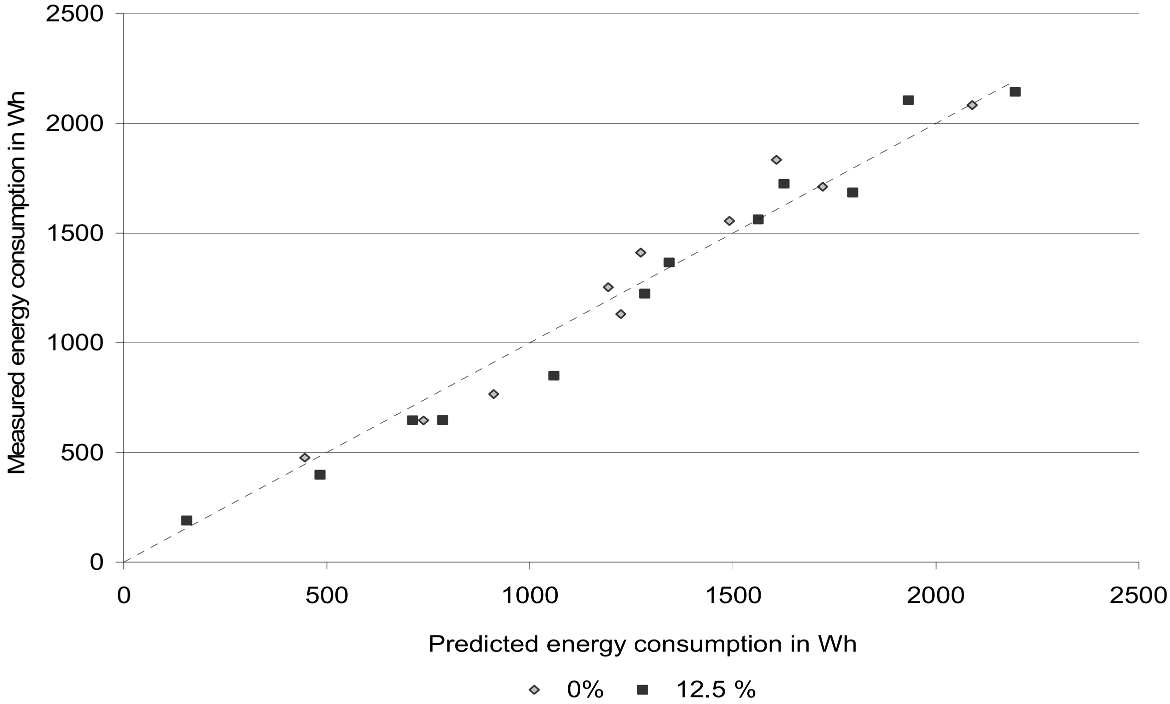

Figure 5-23: Comparison between measured and predicted energy consumption per 24 h under diurnal ambient conditions, appliance 2, load: 0 % and 12.5 % of net volume (the dotted line through the origin shows the expected values if the measured and predicted data totally comply with each other)

For the purpose of computing the energy consumption under dynamic conditions, the overall power consumption was integrated over a period of 24 h using equation 4.15 and 4.17 for refrigerators and refrigerator-freezer combinations, respectively. The target ambient temperature in K, the target internal compartment temperature adjustment in K and the additional heat load were supplied as input variables. Because of the internal temperature adjustment, which based on numbered setting, the average compartment temperature measured on the middle shelf had to be used as an input variable (T_{in}) in the case of appliance 4.

Figure 5-24 to Figure 5-27 graphically highlight a comparison between predicted and measured values under dynamic conditions for the respective appliances. It can be noted that the data points are located on or near the dotted line showing that the predictions are in good agreement with their experimental counterparts. In view of appliance 1 and 4, the highest deviations were found in the middle range (Figure 5-24 and Figure 5-27). Regarding appliance 2 and 3 respectively, the model over- or underestimates the measured values mainly in the upper range (Figure 5-25 and Figure 5-26).

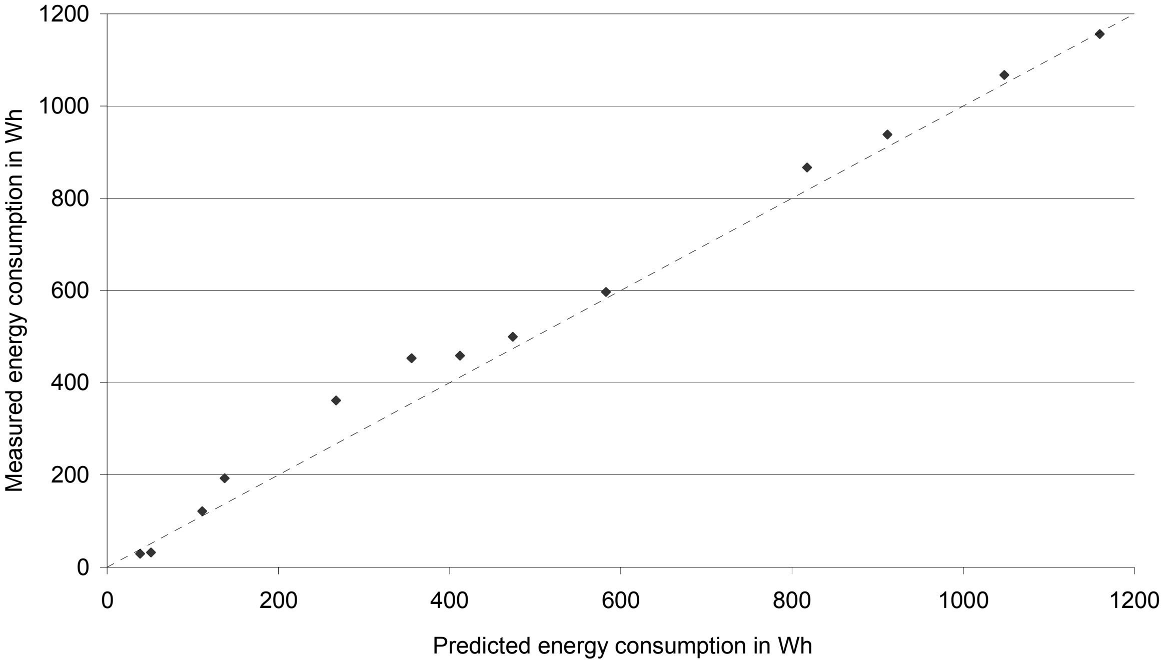

Figure 5-24: Comparison between measured and predicted energy consumption per 24 h under dynamic conditions, appliance 1 (the dotted line through the origin shows the expected values if the measured and predicted data totally comply with each other)

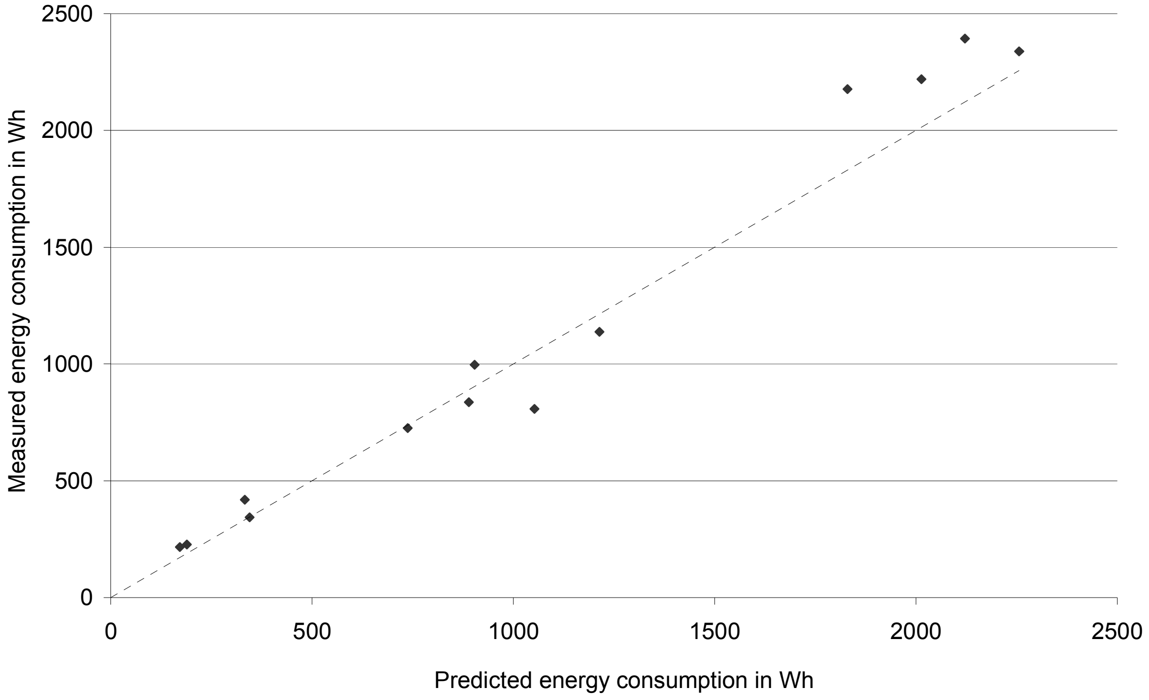

Figure 5-25: Comparison between measured and predicted energy consumption per 24 h under dynamic conditions, appliance 2 (the dotted line through the origin shows the expected values if the measured and predicted data totally comply with each other)

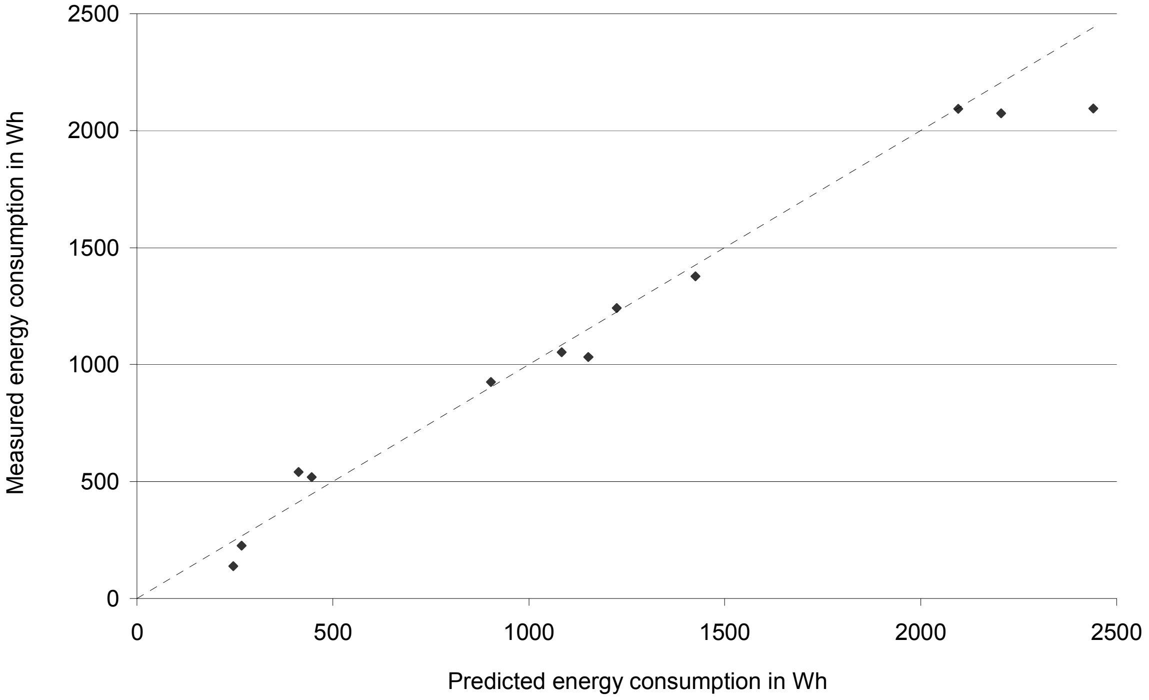

Figure 5-26: Comparison between measured and predicted energy consumption per 24 h under dynamic conditions, appliance 3 (the dotted line through the origin shows the expected values if the measured and predicted data totally comply with each other)

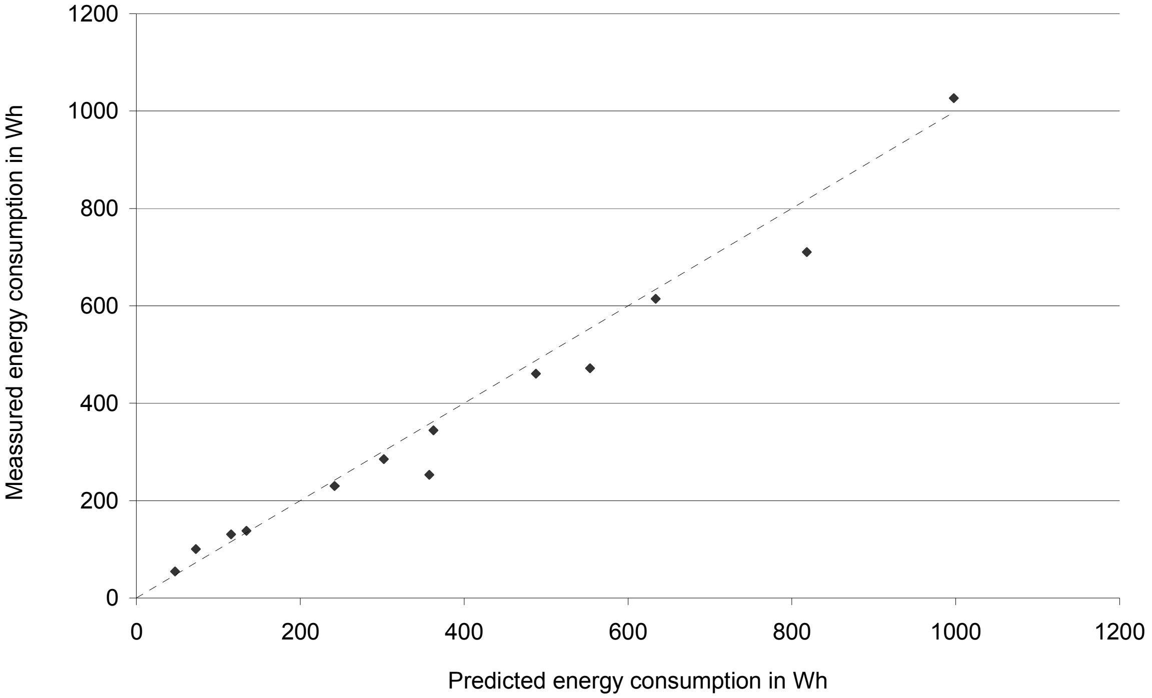

Figure 5-27: Comparison between measured and predicted energy consumption per 24 h under dynamic conditions, appliance 4 (the dotted line through the origin shows the expected values if the measured and predicted data totally comply with each other)

6 Discussion

Although the domestic refrigerators are a frequently investigated topic in context with energy consumption in private homes, the present work takes a special position. In contrast to previous studies, which illuminated the topic either from the technical or from the consumers' point of view, the present study was aiming to combine various perspectives. For the purpose of developing a simulation model that allows predicting refrigerators' energy consumption under real life conditions, it was essential to study both, the consumer behaviour and conditions in private homes and their influences on refrigerators' energy consumption. The main focus thereby was always on covering the entire consumer relevant range. The review of literature was used to identify factors said to be influencing refrigerators energy consumption. These critical factors were of particular importance for all investigations carried out within the scope of the present work.

The discussion of the results will follow the previous sequences starting with the findings concerning the conditions in private homes and the consumer behaviour in handling domestic refrigerators (6.1). In chapter 6.2, the experimental results will be taken up and discussed by comparing them with previous research findings and by evaluating the overall impact of different factors on domestic energy consumption. In chapter 6.3, limitations and potentials with regard to the application of the model will be pointed out and discussed in detail. The discussion of further findings deduced from the present work will be presented in chapter 6.4. The methodological approaches will be critically evaluated and discussed in detail in the respective subchapters.

6.1 Characterisation of real life conditions with regard to domestic refrigerators

As described in earlier studies [EVANS, 1998, THOMAS, 2007] the consumer behaviour in handling domestic refrigerators and the conditions in private homes vary over a wide range. Regarding the ambient temperature of the location, where the cooling appliances are placed, the results reported by the EuP study [EUP PREPARATORY STUDIES LOT 13, 2008] could be confirmed to a great extent by the own investigations. In both studies, a high share of refrigerators were found to be placed in a room with moderate temperatures within the range 20 °C to 30 °C and low variations. Similar values were also measured and reported by THOMAS [2007]. All things considered, however, the range of variation of the ambient temperatures is enormous ranging from 0 °C to over 40 °C. Whereas the temperature values of each country scatter over a wide range, there are also significant differences between the countries. The differences are assumed to be attributable to the different places, where the refrigerators are located in private homes. Most of the appliances seem to be placed in a heated room, for example in the kitchen, with only low diurnal and seasonal temperature variations. Other refrigerators probably are located in an unheated room like a cellar, a balcony or a garage, where the temperature follows pretty much the seasonal changes.

Also with regard to the internal compartment temperature, the results of the online study reflect the range of variation described in literature [LAGUERRE et al., 2002, JAMES and EVANS, 1992b, WORSFOLD and GRIFFITH, 1997]. Most authors reported on compartment temperatures within the range 0 °C to about 12 °C. Also the average temperature values recorded during the in-home study broadly agree with these findings. Small deviations could be due to the small sample size per country.

A high range of variation was also found concerning the door opening behaviour in European households. Data gathered in the online study show frequencies between 0 and over 40 times per day with an average frequency of 11. These results, however, only partly correspond to findings of previous studies, which show markedly higher ranges of variation and mean values. Especially studies based on measurements tend to do so and report on frequencies between 4 and 67 with a mean of 24.7 [THOMAS, 2007] and between 1 and 240 with a mean frequency of 39, respectively [EVANS, 1998]. Other studies, which are also based on guesses, however, revealed small ranges of variation similar to the own findings. This leads to the conclusion that in this special case estimations are not a suitable method to gain reliable data. As a consequence, all following investigations concerning door openings and their influence on refrigerators' energy consumption were based on measured data reported by THOMAS [2007].

When respondents were asked about their loading habits with regard to the main refrigerator, the majority (60.3 %) stated to always or at least sometimes use the full capacity of their appliances (Figure 5-5). A comparison of these statements with the results of the analysis of the pictures, however, shows that nearly the opposite appears to be true. The visual assessment of the pictures revealed that the overwhelming part of observed refrigerators is moderately or only slightly filled (Figure 5-14).

The reason for rising degree of filling with increasing household size is assumed to be the increased demand for foodstuffs. Differences between the countries may be caused by differences in food shopping frequency and the quantities of food purchased each time.

Due to lacking published data on the exact share of used net volume, further calculations were carried out in this context which surprisingly revealed values of at the most 28 %. These data lead to the conclusion that the available net volume of cooling appliances is not used effectively which could be stem from varying geometrical forms of food packages. In this context it could be assumed that a more efficient use of capacity decreases the demand in net volume and raises the demand for smaller appliances with lower energy consumption.

Although several studies have evaluated the food shopping behaviour in Europe and worldwide [EVANS, 1998, COLWILL, 1990, EVANS, 1992, JAMES and JAMES, 2002, JEVSNIK et al., 2008, JAY et al., 1999, KENNEDY et al., 2005a], there are no published data on the quantity of foodstuffs placed into the refrigerator after purchase and the additional heat load caused by this placement. That might be because all previous studies were not undertaken against the background of energy consumption but rather of food safety. The present study, however, aimed to investigate this topic. The quantity of foodstuff put into the refrigerator after purchase was derived from the storage diary. It could be shown that primarily small amounts of goods up to 3 kg are purchased and stored (Figure 5-12). The food shopping frequency, however, was found to be relatively high. Chilled foodstuffs were purchased several times per week by the overwhelming part of respondents (Figure 5-8 and Figure 5-9), which is in line with the findings of THOMAS [2007] and EVANS [1992, 1998]. Nevertheless, it must be noted that the own results potentially do not reflect the conditions in all parts of the countries. The study was conducted in major cities and the suburban areas, where famously the density of grocery stores is much higher and consequently the distances to reach them much shorter than in rural areas. It might be assumed that this fact also influences the shopping frequency and, as a consequence, the amounts of foodstuffs purchased each time.

The derivation of the heat load caused by the placement of new food after purchase is mainly based on assumptions and scenarios concerning the product temperatures. As a consequence, the obtained values have to be seen rather as a crude approximation than as exact data. Nevertheless, the underlying scenarios are not fictional but are derived from conditions described in literature. The time lapse from retail store to the domestic refrigerator, for example, was assumed to vary within the range 30 to 90 minutes, which is in line with the findings of several authors [EVANS, 1992, THOMAS, 2007, KENNEDY et al., 2005b, JAY et al., 1999]. The scenarios concerning the ambient temperatures during transport are based on country-specific climatic data and could thus also be regarded as reliable. Additionally, the calculated increases of product temperatures are in good agreement with the observed values by EVANS [1998].

To measure and record the temperature of each product before placement into the domestic refrigerator surely would have generated even more reliable data. Due to the fact that this kind of measurements would have added a disproportionate workload on the participants, which assumedly would have decreased the willingness to participate, this method was not applied in the present study.

In order to cover a large part of the range of variation, further investigations on the influence of additional heat load on refrigerators' energy consumption are based on the 95. percentiles presented in Figure 5-13. The differences between the countries mainly stem from different ambient temperatures during transport and from different internal compartment temperatures.

Additional heat load can also be caused by placement of cooked food which is not allowed to cool down before. The results of the online study show that the majority of respondents always or mostly allow hot food to cool down before putting it into the refrigerator. In total, 17.1 % of participants stated to never or sometimes act in this way. The additional heat load caused this way was not gathered during the present study.

To conclude, both methods applied to gather the conditions in private homes and the consumer behaviour in handling domestic refrigerators have proven to be suitable.

To conduct a web-based study could be seen as a crude approximation to the topic. This method offered several advantages and enabled to survey a relatively large sample during a short period of time. Owing to proper screening methods as well as plausibility and consistency checks, biasing effects were minimised to a high extent and data quality was assured. Although the answers of the respondents are based on estimations, they mostly are in line with findings of previous studies. A disadvantage of online surveys is the limited reachability of the retired generation. For this reason, the selection criteria for participants were accordingly adapted and a lower age limit of 55 years was predetermined for elder single households.

The majority of questions contained in the questionnaire of the online survey were designed as closed questions to facilitate coding and analysis of answers. In this way, however, the respondents were only allowed to answer in a predefined manner and they potentially could not find a response that matched their actual opinion or conditions. As a consequence, new issues could not be raised and outlier as well as special behavioural patterns possibly remained undetected. Nevertheless, the study was aiming to gain knowledge about the normal ranges of variation concerning different conditions and behavioural patterns rather than to detect special cases.

The in-home study could be seen as an in-depth analysis of the consumer behaviour in handling domestic refrigerators and chilled food in private homes. Using a combination of diaries, temperature measurements and photos provides detailed information on the variety of conditions and habits and allows checking the results of the online survey for consistency and correctness. Due to the complexity of the study, the sample size had to be limited to 100 households. All households were briefed in detail on how to fill in the diaries and how to take the photos. All in all, the quality of reporting by diaries can conclusively be assessed as good. Towards the end of the observation period, however, there is a slight tendency towards less frequent diary notes in some households showing a decline of interest and diligence. This considerably emphasizes the importance of the length of the field phase that should be neither too long nor too short. At the beginning of each observation period the so called Hawthorne effect[6] [COURAGE and BAXTER, 2005] can be expected to modify the results. After this initial stage the participants normally experience a phenomenon of habituation that makes them forget the observation [BIERMANN, 2006]. As a consequence, the field phase in this case should take at least several days to reach the second stage. On the other hand, the willingness to participate declines with increasing length of time, accompanied by a decreasing diligence. Considering all these effects, the field phase of the present study was limited to fourteen days in order to include two weekends. This period was found to be still reasonable to gather reliable data.

In order to reduce the participants' workload and to increase their compliance, pre-printed diaries were provided to them and they were also allowed to use common household measures to indicate amounts. Concerning the placement of new food, respondents were more likely to indicate the net weight of each product printed on the packaging. Reporting the quantity of foodstuffs removed from the refrigerator, however, the participants especially made use of the common household measures.

6.2 Effect of different factors on refrigerators' energy consumption

In the present study, the impact of different factors said to influence refrigerators' energy consumption was investigated. Additionally, the influence of diurnal temperature variations on the energy consumption of cooling appliances was analysed

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[6] The Hawthorne effect is a phenomenon in which persons change one or more aspects of their behavior in response to being observed

for the first time. In contrast to previous studies, which examined the effect of different factors separately and within narrow, artificial ranges, this study was aiming to reflect actual conditions by analysing each factor within the whole range of variation.

The factors were investigated using design of experiments. The applied Box-Behnken design reduced the number of factor combinations required to evaluate the effects of three factors on the response to 13 per appliance and experimental series. The central point was additionally replicated at least two times. Quadratic polynomial equations for predicting refrigerator's energy consumption were developed enabling the final determination of the most influencing factors.

The assertion reported by MEIER [1995], SAIDUR et al. [2002] and other authors that the ambient temperature account for the overwhelming part of refrigerators' energy consumption can be confirmed by this study. This factor was found to be significant across all investigated appliances and experimental series (Table 5-2, Table **5-4** and Table 5-6). Also the regression equations, which are presented in terms of coded factor, show the huge effect of this factor in relation to the other factors (Equations 5-1 to 5-12).

Contrary to the findings of MEIER [1995], who reports on a linear correlation between the ambient temperature and the energy consumption, the present analysis revealed a quadratic relationship. This pretended discrepancy, however, is traceable to the temperature ranges, in which the measurements were carried out. Whereas the ambient temperature was varied within a relatively narrow range (18 °C to 29 °C) in the study by MEIER [1995], the present study covered the interval between 5 °C and 40 °C. Close inspection revealed that the developed quadratic model can be linearly approximated within the narrow range.

The importance of the ambient temperature can be explained by the conduction through the cabinet walls, which largely depends on the ambient temperature. Moreover, the compressor's efficiency declines with rising ambient temperatures, which additionally enhance the effect of this factor. [ASHRAE, 2002, SAIDUR et al., 2002]

Nevertheless, the conduction is not only dependent on the ambient temperature but also on the internal compartment temperature. This may be the reason why this factor is also significant across all appliances. The regression equations in terms of coded factors (Equations 5-1 to 5-4), however, show that its effect is considerably lower than the effect of the ambient temperature. These results correlate well with the literature [LEPTHIEN, 2000, MEIER, 1995].

Additionally, it can be derived from the regression equations that the compartment temperature has a negative effect on the energy consumption. That means that the energy consumption increases with decreasing temperatures and vice versa. Appliance 4, however, seems to be an exception. In this case, the regression equation indicates a positive relation between both variables. This pretended discrepancy is related to the temperature adjustment dial. In contrast to the digital thermostat of appliance 1 to 3, the internal temperature of appliance number 4 has to be adjusted by means of a control knob marked with numbers, whereas the higher numbers represents lower temperatures.

The internal compartment temperature was additionally found to be involved in the interaction with the ambient temperature. Whereas a decrease in compartment temperature has almost no effect at low ambient temperatures, it significantly increases the energy consumption at high ambient temperatures (Figure 5-15). The interaction effect of both factors is shown to be significant across all appliances under static conditions with the exception of appliance 3 (Table 5-2). In contrast to all other refrigerators tested, appliance 3 is equipped with a so called winter-switch, which automatically heats the fridge compartment by means of the internal light bulb if the ambient temperature falls below a specific limit. This additional energy input forces the compressor to start more frequently and so it saves the freezer compartment from defrosting. Winter-switches are only used in refrigerator-freezers with one compressor and without magnet valve. This mechanism consumes additional energy, which obscured the interaction effect between the ambient temperature and the internal compartment temperature in the case of appliance 3.

In accordance with the findings of a previous study [BANSAL, 2001], the refrigerators' load was found to have almost no influence on the energy consumption. The results of the ANOVA (Table 5-2) clearly show that this factor is statistically not significant across all appliances. The perturbation plots (Figure 5-17) also graphically highlight that there is almost no effect of varying the amount of load on refrigerators' energy consumption. Nevertheless, the effect was tested only under static conditions, without door openings and placement of new items. Further studies will have to show whether these results can also be transferred to dynamic conditions.

The results of both empirical studies carried out within the scope of the present work show that several cooling appliances are located in an unheated room, where the temperature more or less follows the diurnal variations. For this reason, the effect of diurnal temperature variations was tested in laboratory. The experiments revealed that the energy consumption is highly sensitive to any variations in ambient temperature. As described above, the energy use largely depends on the conduction through the cabinet wall, which is determined, amongst others, by the difference between the ambient and the internal compartment temperature. Diurnal temperature variations induce a temporary increase in this difference and as a consequence, are responsible for additional energy consumption.

Regarding the additional heat load caused by the placement of new foodstuffs, the results of the ANOVA (Table 5-6) show a significant influence on refrigerators' energy consumption across all appliances tested. Taking a closer look at the 3D plots (Figure 5-19) and the regression equations in terms of coded factors (Equation 5-9 to 5-12), it is evident that the effect of additional heat load is considerably lower than the effect of the ambient temperature. Even though a direct comparison of these results is not possible due to differences in experimental design, studies by MASJUKI et al. [2001], SAIDUR et al. [2000], VHK [2005] and HASANUZZAMAN et al. [2008] also revealed a slight increase of energy consumption caused by the placement of warm items.

In accordance with the literature [VHK, 2005, MEIER, 1995, SAIDUR et al., 2002, PARKER and STEDMAN, 1993, KAO and KELLY, 1996], the impact of door openings on refrigerators' energy use was found to be small. This is because of the low heat capacity of the exchanged air. Nonetheless, their effect increases with rising ambient temperatures (Figure 5-20 and Figure 5-21), which can be explained by the fact that the cold air inside the fridge compartment is exchanged by warm and moist air from outside when door is opened. As a consequence, the additional heat load caused by a door opening largely depends on the ambient temperature.

The additional energy consumption per litre of net volume was in the same order of size for both appliances. However, differences could be identified in view of the percentage increase in energy use. Whereas the energy consumption rises by 0.4-0.44 % per door opening in the case of appliance 1, an increase of 0.12-0.19 % can be observed in the case of appliance 2 within the investigated ranges. These differences can be attributed to the different net volume of both appliances. Moreover, appliance 2 is a fridge-freezer, whose energy consumption is highly dependent on the freezer compartment. As a consequence, the effect of openings of the fridge compartment door might disappear to a large extent.

The experimental conditions of all experiments conducted within the scope of the present work based as far as possible on those defined in the EN 15502:2005 standard in order to enhance both, repeatability and reproducibility.

6.3 Application of the simulation model and its potentials and limitations

The own developed simulation model is based on the findings of the laboratory experiments and so it incorporates all factors that have a significant impact on refrigerators' energy consumption. For the purpose of qualitative assessment of the simulation model, the measured energy consumptions were compared to the respective calculated values (Figure 5-22 to Figure 5-27). Regarding these comparisons, it can be concluded that the model is well suitable for the prediction of energy consumption of refrigerators and refrigerator/freezer combinations throughout the whole consumer-relevant range. The model predicts almost all values within a ±10 % deviation band. In this context, it is noteworthy that experimental uncertainties of the conducted energy consumption tests are partially higher than ±10 % due to the complexity of the experiments. This additionally endorses the validity of the developed model.

Altogether, no systematic over- or underestimations became apparent. Under extreme conditions, however, that means at very high ambient and very low internal temperatures in combination with high additional heat loads, the model possibly overestimates the required energy (cf. Figure 5-22 and Figure 5-26). This potential failure can be explained by the fact that especially the compressors of recent and highly efficient fixed speed cooling appliances are likely to be unable to cope with the complete heat load even though they are operating continuously under such extreme conditions. These extreme conditions surely must be seen as an exception rather than a rule in private homes so that no importance should be attached to this deficit of the model.

Generally, the model tends to predict the energy consumptions of refrigerators more accurately than those of combined refrigerator-freezers. This may be due to the assumptions made in the case of refrigerator-freezers. The efficiency factor η^*, for example, which is considered as identical for both compartments, is likely to vary in reality. Also the thermal conductivity, the wall thickness and the surface area of both compartments might be actually not equivalent. These assumptions may also be responsible for the magnitude of the weighting factor α, which does not represent the actual shares of both compartments on the energy use of refrigerator-freezer combinations. In view of these facts, additional investigations and adjustments could further improve the prediction accuracy of the model with regard to combined appliances.

To the best of my knowledge, this is the first model that allows predicting the energy consumption of domestic cooling appliances under real life conditions. Previous modelling approaches [HERMES et al., 2009, HERMES and MELO, 2009, BORGES et al., 2011] predominately aimed to assess the influence of various engineering design parameters on refrigerators' energy performance. In contrast to these models, the present approach only requires comparatively few input factors, which are further ascertainable without additional high experimental expenditure. The required constants x and y, for example, can be derived from the average condenser and evaporator temperatures, which are usually measured by the manufacturer during the process of product development or product testing. The same applies for the thermal conductivity coefficient λ. Additional experiments, however, have to be conducted in order to detect the input variables η^* and α (in the case of refrigerator/freezer combinations) by means of the least square method. Nevertheless, these experiments have to be conducted under static conditions and so the additional expenditure may be considered as low.

Owing to the limited number of input factors, the developed model could be applied in consumer counselling and consumer education to visualize the influence of different conditions and behavioural pattern on refrigerators' energy consumption. Moreover, manufacturers of domestic cooling appliances could use this approach in product development in order to quantify benefits for customers. The model could also be applied at the point of sale complementary to the Energy Label for the purpose of providing information on the actual energy use of different appliances under the respective relevant conditions. This would imply the creation of a database containing all required information on recent cooling appliances and the software-based implementation of the modelling approach. In addition, the present approach should be evaluated in view of its suitability for application in energy labelling worldwide. Due to the obligation of manufacturers to test their appliances according to all standards of the market, in which they are offered for sale, there have been several approaches in recent time to make this process easier [BANSAL and KRUGER, 1995, BANSAL, 2003, HARRINGTON, 2009]. In this context, the model should be checked for its suitability to translate the energy consumption of a cooling appliance from one test procedure to another in order to avoid expensive and time-consuming tests and to facilitate international trade.

Before implementation, however, it is important to know whether the developed model and the results gained can be generalized. Although the energy consumption predicted by means of the developed model is in good agreement with measured data, it has to be considered that only four different appliances were tested during the study. Indeed, the investigated appliances vary, amongst others, in type, size, temperature control, energy efficiency class, climate class and cooling system. Nonetheless, it would be appropriate to conduct further experiments with domestic refrigerators and refrigerator-freezers of different brands and features in order to test the developed model for possible transfer to other cooling appliances.

6.4 Further findings deduced from the present work

The Energy Label of domestic refrigerator is criticised time and again by experts and consumer bodies for not representing real use conditions [MTP, 2006]. Criticism especially focuses on the lack of door openings. In view of the results of the present work, however, it is evident that it is virtually impossible for a label to meet real use conditions due to their complexity and diversity.

By linking consumer behaviour as well as actual conditions and energy consumption tests in laboratory, the present study revealed that refrigerators' energy consumption is highly variable and sensitive to consumer behaviour and conditions in private homes. The daily energy consumption of one and the same appliance might vary from almost 0 Wh to 2000 Wh and even more dependent on the respective conditions and appliances. The influence of door openings and degree of filling, however, whose lack is the main point of criticism concerning the current Energy Label test procedure, was found to be vanishingly low. In view of this fact and the fact that more complex test procedures are likely to suffer losses of reproducibility and repeatability and are complicated to perform [WIEL and MCMAHON, 2005], it might be advisable to maintain the current energy test procedure as a compromise. The labelled energy use has to be regarded rather as a benchmark that allows comparing different appliances than as an exact value.

Besides the energy consumption of cooling appliances, there is a further aspect which is highly dependent on the consumer behaviour and the conditions in private homes: the internal temperatures and associated with that the food hygiene. According to the findings of a previous study [MTP, 2006], it was found within the scope of the present study that some highly efficient fixed speed appliances without special chill compartments have long cycling times and are not particularly sensitive to a rise in internal temperatures. Such appliances might be unable to cope with the complete heat load, caused by placed warm foodstuffs, within a reasonable period of time even though they are operating continuously. As a consequence, the cooling process of warm food may take a long time and chilled foodstuffs may warm up in the meantime. To date, neither the microbial consequences nor the frequencies and conditions of occurrence of this problem are analysed. For this reason, further research should be devoted to explore these aspects and to develop a model for predicting internal temperatures and food safety under real life conditions.

7 Conclusion

The main aim of this thesis has been to develop a model that allows predicting the energy consumption of domestic refrigerators under real life conditions in Europe. The emphasis thereby was on covering the entire consumer-relevant range. This also included the subordinate aims to determine empirically the relevant range of ambient and using conditions of domestic refrigerators in private homes and to analyse the effect of the usage behaviour on the energy consumption of the appliances.

By means of a survey of a random sample of 1000 consumers and an in-home study with 100 participants in Europe, the actual state concerning ambient and using conditions of domestic refrigerators in private homes was recorded. The results of the empirical studies showed that ambient conditions in private homes as well as consumer habits in handling chilled foodstuffs and domestic refrigerators vary greatly. Differences were not only apparent between different countries or types of households but also on an individual level. The main findings could be summarized as follows:

- Ambient temperatures varied between almost 0 °C and more than 40 °C depending on the respective location of the appliances. Although the ambient temperature was found to be relatively constant over the year in the majority of investigated households, some appliances were subjected to great diurnal and seasonal variations in temperature.
- The internal compartment temperature adjustment showed significant differences between the investigated countries. In general, consumers in Great Britain and Spain were found to choose lower temperatures than consumers in France and Germany. In total, the temperature setting indicated by the participants of the survey varied within the range 0 °C to 12 °C with a median of 4 °C.
- Loading efficiency was assessed to be low. The visual analysis of the pictures of refrigerators’ internal spaces revealed that less than 30 % of appliances were filled to their full extend. Moderate load was observed in most of the

investigated households, whereas slightly filled appliances were especially found among young singles. Even if refrigerators were assessed as fully loaded, they used less than 30 % of the net volume indicated by the manufacturer.

- The amount of additional heat load caused by placement of food after purchase largely depends on the transport time and on the ambient temperature during transport. Previous studies stated that only a few of consumers used an insulated bag or box for transport of perishable foodstuff. Based on this knowledge, additional amounts of heat load ranging from nearly 0 kJ up to 1700 kJ per purchase were calculated in the present study.

Based on the results of the empirical studies, typical ambient and using conditions of cooling appliances were simulated in laboratory within the entire consumer relevant ranges in order to determine the influence of different parameters on the energy consumption of domestic refrigerators. In total, two different refrigerators and two refrigerator-freezers were tested under various ambient conditions and usage factors. It could be shown that the ambient temperature is responsible for the overwhelming part of energy consumption of an appliance. The energy was also affected, to a minor degree, by the internal compartment temperature adjustment and an additional heat load. The experiments additionally revealed a significant effect of variations in ambient temperature on refrigerators' energy consumption. The degree of load of a cooling appliance, however, was found to have almost no impact under static conditions. In consequence of a low specific heat capacity of air, the same applies to door openings.

The results obtained by the laboratory experiments under static conditions served as a basis to develop a simplified model for predicting energy consumption of refrigerators and refrigerator-freezer combinations. The proposed model approach was validated against experimental energy consumption data measured under dynamic and thereby realistic conditions. Comparisons of the model predictions with their experimental counterparts showed good agreements. Although almost all derivations were found to be within a 10 % error band, it is worth noting that the proposed model predicted the

energy use of refrigerators more accurately than that of refrigerator-freezers. This could be a starting point for further investigations.
It has to be reminded that the applicability of the proposed model was only tested on the basis of four different appliances. Future work has to show to which extent this approach is applicable to other kinds of domestic cooling appliances.

The present work provides comprehensive data in view of ambient and usage conditions of domestic refrigerators in private homes. As these conditions may not only influence the energy consumption of the appliances but also the quality and safety of stored foodstuffs, a focus of further research should be laid on the simulation of home storage practices to assess their impact on shelf life and food quality.

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List of abbreviations

A	surface area in m^2
AHAM	Association of Home Appliance Manufacturers
ANOVA	Analysis of variance
ANSI	American national Standards Institute
ANZS	Australian-New Zealand Standard
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
C	Celsius
cf.	confer
CFC’s	chlorofluorocarbons
CNS	Chinese National Standard
COP	coefficient of performance
CR	Carnot Refrigerator
c	specific heat capacity in $kJ \cdot kg^{-1} \cdot K^{-1}$
d	day
df	degrees of freedom
DIN	Deutsches Institut für Normung (German Institute of Standardization)
DOE	Department of Energy
EEA	European Economic Area
e.g.	for example
EN	European Norm
et al.	et alii
F	Fahrenheit
FC’s	fluorocarbons
g	gramme
GWP	global warming potential
h	hour

HFC's	hydrofluorocarbons
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ISO	International Standard Organization
JIS	Japanese Industrial Standard
K	Kelvin
k	material dependent decay constant that governs the rate of cooling per minute
kWh	kilowatt hour
l	litre
max	maximal
MEPS	minimum energy efficiency standards
min	minimal
ml	millilitre
MLR	multi linear regression method
n	sample size
ODP	ozone depletion potential
p	significance level
P_{off}	power consumption during compressor off-cycle
PRESS	predicted residual sum of square
Prob	probability
Q	amount of heat in kJ
Rf	refrigerator
RFC	refrigerator-freezer-combination
RH	relative humidity
R^2	coefficient of determination
R-134a	tetrafluoroethane
R-600a	isobutene
SS_M	mean sum of square
SS_R	residual sum of square
T	temperature

t	time
T_H	temperature of the higher isotherm
T_L	temperature of the lower isotherm
V	voltage
W	watt
x	constant offset between T_H and T_{out}
Y	response
y	constant offset between T_L and T_{in}
ZVEI	Zentralverband Elektotechnik- und Elektronikindustrie (German Electrical and Electronic Manufacturers' Association)

Greek symbols

α	weighting factor
β	coefficient of regression
Δ	difference
δ	thickness of solid
ε	residual error
η^*	efficiency factor
λ	thermal conductivity in $W \cdot K^{-1} \cdot m^{-1}$
ϑ	temperature

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