Institut für Landtechnik

Professur für Haushalts- und Verfahrenstechnik

Prof. Dr. rer. nat. Rainer Stamminger

Sustainable use of washing machine: modeling the consumer behavior related resources consumption in use of washing machines

Inaugural–Dissertation

zur

Erlangung des Grades

Doktor der Ernährungs- und Haushaltswissenschaft
(Dr. oec. troph.)

der

Landwirtschaftlichen Fakultät

der

Rheinischen Friedrich-Wilhelms-Universität Bonn

vorgelegt am 27.02.2014

von

Dipl. oec. troph. Emir Lasic

aus

Sanski Most, Bosnien und Herzegowina

Referent: Prof. Dr. rer. nat. Rainer Stamminger

Korreferent: Prof. Dr. Michael-Burkhard Piorkowsky

Tag der mündlichen Prüfung: 25. 04. 2014

Erscheinungsjahr: 2014

Abstract

Sustainable use of washing machine: modeling the consumer behavior related resources consumption in use of washing machines

Two opposing trends are observed in Europe: an increase in the washing machines' rated capacity and a decrease of the household size (hence a decrease of laundry that has to be washed). The question poses: what kind of behavior is necessary to use the washing machines with a higher rated capacity in a more sustainable manner? To answer this question, a model of a washing machine (virtual washing machine) that is based on real data of real-life washing machines is constructed. Furthermore, a model that reproduces, to some extent, the household's washing behavior (virtual washing household) is developed.

By conducting parallel simulations of the usage of the virtual washing machine by the virtual washing households and by varying device-, household- and behavioral parameters, an optimal parameter combination with the lowest environmental impact is determined.

The basis for the virtual washing machine is the data gained by testing nine washing machines of different rated capacity (5 *kg*, 6 *kg*, 7 *kg*, 8 *kg* and 11 *kg*). All tests are conducted in accordance with EN60456:2005, with some modifications regarding the washing temperatures, load size and detergent dosage.

The predicting power of the virtual washing machine can be considered as good, given that there are numerous differences in tested washing machines.

The virtual washing household is designed in such a manner that a washing cycle is conducted when the household has enough laundry collected, so that the rated capacity of the washing machine can be used. It also offers a possibility to conduct an "emergency washing cycle" when the time needed for accumulating enough laundry (to use rated capacity of the washing machine) exceeds the waiting time acceptable by the consumer (so-called "maximal laundry waiting time"). This model offers a large range of possibilities to simulate some of the consumer's behavioral patterns.

With the moderating variable “maximal laundry waiting time”, it is possible to add a time dimension to the virtual consumer model and thus explore the effects that might occur when the consumer is ready to postpone an action (in this case the washing of laundry) to a later point of time. The results show that a sustainable use of washing machines with a higher rated capacity is possible when consumer behavior changes towards waiting until enough laundry is accumulated, so that the rated capacity of the washing machine is used.

Zusammenfassung

Nachhaltige Nutzung einer Waschmaschine: Modellieren des verhaltensabhängigen Ressourcenverbrauchs bei der Waschmaschinennutzung

Zurzeit sind zwei Trends in Europa zu verzeichnen: einerseits erhöht sich die Anzahl der Waschmaschinen mit einer höheren Nennfüllmenge und anderseits verringert sich die Größe der Haushalte und somit der Wäscheanfall. Es stellt sich nun die Frage: „Wie kann ein Haushalt mit einer kleinen Personenanzahl eine Waschmaschine mit einer höheren Nennfüllmenge dennoch nachhaltig nutzen?“

Um diese Frage beantworten zu können, wird in dieser Arbeit zunächst, auf Basis von Daten handelsüblicher Waschmaschinen, ein mathematisches Modell einer Waschmaschine entwickelt (virtuelle Waschmaschine). Des Weiteren wird ein Modell eines Haushaltes entwickelt, welches bis zu einem gewissen Grad das Waschverhalten des Haushaltes nachahmt (virtueller Waschhaushalt).

Mittels paralleler Simulationen der Nutzung der virtuellen Waschmaschinen durch den virtuellen Waschhaushalt und Veränderung der Geräte-, Haushalts- und Verhaltensparameter werden geeignete Parameter-Kombinationen gesucht, bei welchen die Auswirkungen auf die Umwelt am niedrigsten sind.

Die Basis für die virtuelle Waschmaschine bilden Daten aus Waschmaschinentests mit 9 Waschmaschinen verschiedener Nennfüllmengen (5 kg, 6 kg, 7 kg, 8 kg und 11 kg). Alle Tests werden in Anlehnung an die EN60456:2005 durchgeführt, wobei Waschtemperatur, Beladungsmenge und Waschmittelmenge modifiziert werden.

Trotz der Vielfalt der Waschmaschinen und den Unterschieden zwischen diesen, kann die Vorhersagekraft der virtuellen Waschmaschine als gut bewertet werden.

Der virtuelle Waschhaushalt ist so gestaltet, dass ein Waschgang erst dann durchführt wird, wenn genug Wäsche vorhanden ist, um die Nennfüllmenge der Waschmaschine komplett auszunutzen. Des Weiteren bietet das Modell die Möglichkeit, einen sogenannten „Notwaschgang“ durchzuführen. Dieser findet dann statt, wenn die Zeit, welche nötig ist um genug Wäsche zu sammeln, die vom Verbraucher akzeptierte Wartezeit (sogenannte „Maximale Wäschewartezeit“) überschreitet.

Dieses Modell ermöglicht die Simulation vieler verbrauchertypischer Verhaltensmuster.

Mit der moderierenden Variablen „Maximale Wäschewartezeit“ ist es möglich, die zeitliche Komponente in das Verbraucher-Modell einzubeziehen. Dadurch können mögliche Effekte aufgezeigt werden, wenn der Verbraucher bereit ist, eine Handlung (in diesem Fall Wäschewaschen) auf einen späteren Zeitpunkt zu verschieben.

Die Ergebnisse zeigen, dass eine nachhaltige Nutzung der Waschmaschine mit einer höheren Nennfüllmenge dann möglich ist, wenn der Verbraucher das eigene Verhalten dahin gehend verändert, dass er wartet, bis sich genug Wäsche angesammelt hat und so die Nennfüllmenge der Waschmaschine ausgenutzt werden kann.

Content

1 Introduction

Laundry washing, in the sense of cleaning textiles in aqueous liquor, is a complex process involving the cooperative interaction of numerous physical and chemical influences. In the broadest sense, washing can be defined as both removal by water or by an aqueous detergent solution of poorly soluble residues, as well as the dissolution of water-soluble impurities. (JAKOBI and LÖHR, 1987, SMULDERS *et al.*, 2007)

TERPSTRA defines the primary objective of cleaning as "…restoration of the fitness for use and the esthetical properties of the textiles, e.g. removal of soil, stains, odors and creases and regaining surface smoothness and thermal isolation." (TERPSTRA, 2001, p.4) LEMARE defines other benefits from laundering processes, such as the maintenance of the appropriate hygiene (LEMARE, 1987).

1.1 Washing process

The washing process is described as a function of different: washing temperatures, length of washing cycles, types and amounts of detergent and applied mechanical works. It is best described by using a circle, which many researchers today refer to as *Sinner's Circle* (Figure 1-1). (SINNER, 1960) STAMMINGER adds a further fifth parameter, water (inner circle), which represents the combining element of all factors (STAMMINGER, 2013).

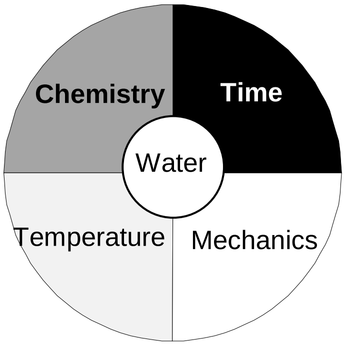

Figure 1-1: Sinner's circle (own representation)

Each of these four factors can be substituted to a certain degree by the other three factors and the resulting washing performance remains the same. For example, a decrease of the temperature can be partially compensated by increasing either one or more of the other factors, i.e. chemistry, washing time or mechanical agitation. (WAGNER, 2011, KUTSCH *et al.*, 1997, SMULDERS, 2007)

The combination of different factors depends on the washing technique employed. In the case of washing laundry by hand, the portion of the mechanics is much higher than the portion of the washing time (Figure 1-2). Laundry washing in a washing machine at a higher temperature results in a higher contribution of the temperature in the washing process (Figure 1-3).

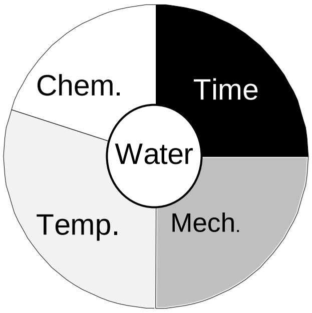

Figure 1-2: Sinner's circle for washing by hand (own representation)

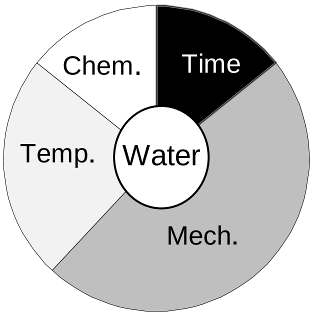

Figure 1-3: Sinner's circle for washing in a washing machine at a high temperature (own representation)

1.1.1 Mechanics

In the washing process, the textiles are mixed with the wash liquor. The total amount of wash liquor required in the main wash process is made up of two portions: liquor soaked by the laundry (*bound wash liquor*) and liquor that remains free in the drum (*free wash liquor*). (SMULDERS *et al.*, 2007) In the case of manual laundering, the mechanical action is done by rubbing and beating, stretching and squeezing of the textiles. Sometimes this is done by using auxiliary devices. (SMULDERS *et al.*, 2007)

In washing machines, the mechanical work is determined by: diameter of the drum, reverse rhythm, water level, number of revolutions of the drum, position and number of the paddles in the drum, the amount of load, and the duration of the wash cycle. (HLOCH *et al.*, 1989)

The extent of the mechanical action imparted to the laundry can be altered by changing the ratio of dry laundry weight to the volume of wash liquor (*laundry-liquor-ratio*). A low wash liquor level and relatively rapid reversal causes a large mechanical effect on the laundry. In contrast, a high wash liquor and slower reversal provides less mechanical action. (SMULDERS *et al.*, 2007)

1.1.2 Temperature

With an increase of the temperature, the soil removal normally increases. The elevated temperature enhances the chemical reactions, solubilizes greasy soils and weakens the binding forces of the soil on the fabric. (SMULDERS *et al.*, 2007)

The maximal washing temperature is determined by the properties of the wash load. With an increase of the temperature, the soil-binding capacity of the wash liquor decreases, so that an extensive soil redisposition can be anticipated. Furthermore, with an increase of the temperature, the knitting of the synthetic fibers increases as well.

In order to prevent those opposing trends in the praxis, the laundry washing process is divided into different sub-processes. Today, normally the laundry washing is divided into prewash and main wash, which is followed by the rinsing cycle. (HLOCH *et al.*, 1989)

1.1.3 Washing time

In order to remove the dirt from the textiles, the washing factors of chemistry and mechanics have to interact together with the load at a certain washing temperature for a certain period of time (WAGNER, 2011).

The duration of the washing process determines how long the detergent is allowed to act. Longer cleaning times will increase the soil removal and thus improve the cleaning performance (VAUGHN *et al.*, 1941).

At the beginning of the washing process, it is necessary to heat up the cold inlet water. Heat-up time is the time required to achieve the preset temperature. Heat-up time depends on the amount of laundry and hence the water quantity, the temperature of the inlet water and the heating capacity of the washing machine. This heat-up time is followed by the main washing time. (KUTSCH *et al.*, 1997, SMULDERS, 2007, WAGNER, 2011)

1.1.4 Chemistry

The factor chemistry is accompanied with the medium water. A quantifying of this factor in the form of a single operand is not possible since the washing chemistry does not only depend on the very complex coaction of different detergent components, but also depends on other factors, such as temperature or soil composition. (HLOCH *et al.*, 1989)

Besides the actual removal of soil, further functions of the chemical substances are: water softening, emulation of lipid component, dispersion and stabilization of particulate soil, bleaching of stains and dissolving of proteins. (KUTSCH *et al.*, 1997)

The washing performance normally increases as the detergent concentration increases. When the detergent concentration is too high, the washing performance decreases, because a high foam production leads to a decrease of the mechanical force. (HLOCH *et al.*, 1989)

1.2 Washing machines

Washing machines that are presently used globally in domestic laundry care can be divided mainly into two categories depending on the orientation of their axis: horizontal and vertical axis washing machines. Following are the different types of those automatic-washing systems. (KUTSCH *et al.*, 1997)

1.2.1 Horizontal axis washing machine

This type of washing machine consists of a stainless steel, perforated drum into which the laundry is loaded, and an outer surrounding tub into which the water is filled. The mechanical agitation of the laundry is done by rotating the drum around a horizontal axis. Paddles, which are mounted on its inside, lift the laundry to the top and then let it tumble down. (WAGNER, 2011; KUTSCH *et al.*, 1997; SMULDERS, 2007)

Because the wash action does not require the clothing to be fully suspended in water, only enough water is needed in order to moisten the fabric and to ensure a sufficient transfer of suds between the water-soaked laundry and the free water. An electric heater element on the bottom of the drum allows the heat-up of the water in the main wash phase to the preset washing temperature, mainly between 30 °C and 60 °C. (WAGNER, 2011; KUTSCH *et al.*, 1997; SMULDERS, 2007)

Today’s state of the art domestic washing machines have many features built in, such as a large number of different programs for all kind of textiles, automatic detection of amount and type of textile, automatic dosing, steam generator for laundry refreshing purposes, etc. (WAGNER, 2011; KUTSCH *et al.*, 1997; SMULDERS, 2007)

Furthermore, modern washing machines frequently use the so-called fuzzy logic control which governs partial processes of the washing program. Such a control is able to automatically provide, for example, variable speeds of reversion of the drum depending on the amount of foam produced during the wash cycle, or to control the quantity of water intake and washing time depending on weight and type of wash load. All those features should help the consumer to treat the laundry optimally. (SMULDERS *et al.*, 2007)

The horizontal axis type of washing machine is mainly used in Europe and Near East countries. In recent years, this type of machine has also been gaining market shares in all other regions as well. (WAGNER, 2011; KUTSCH *et al.*, 1997; SMULDERS, 2007)

1.2.2 Vertical axis washing machine

This type of washing machine uses a vertically mounted perforated drum that is itself contained within a watertight tub. The laundry is freely suspended in the water. The mechanical work is performed by moving the laundry in the water. Depending on its laundry motion configuration, these washing machine can be subcategorized into:

1.2.2.1 Impeller (pulsator) type washing machine

In this type of machine, an impeller located on the bottom of the washing machine induces a vortex. The vortex causes the laundry to circulate up and down in the water. This type of washing machine is common in Japan, China and South Korea. These machines normally do not contain a heating element, but use cold (or otherwise preheated) water from the tap. (WAGNER, 2011; KUTSCH *et al.*, 1997; SMULDERS, 2007)

1.2.2.2 Agitator type washing machine

In this type of washing machine, the mechanical work is produced by a device (agitator) located in the center of the drum, which then rotates around its vertical axis to the right and left. These machines normally are connected to an external hot and cold water supply and mix these waters accordingly. This type of washing machine is common in the USA and Canada. (WAGNER, 2011; KUTSCH *et al.*, 1997; SMULDERS, 2007)

1.2.3 Washing machine markets and trends

The EU-27 washing machine stock in the residential sector was estimated to be around 172,85 million units (Bertoldi and Atanasiu, 2007). According to data presented in the Preparatory Study for Eco-design Requirements of Energy-using Products (EuP) the penetration of the washing machines on the European market is high: Germany (96 %), Czech Republic (94,9 %), Poland (86 %), 87, France (94,7 %), Hungary

(88 %), Spain (98,5 %), UK (94 %) Finland (87 %), Sweden (72 %). (PRESUTTO *et al*, 2007)

The share of washing machines with a higher rated capacity has grown in the past years. On the European market, the average washing machine load capacity has increased from 4,8 kg in 1997 up to 5,4 kg in 2005 (CECED, 2005) and is still increasing. In 2010, washing machines with a rated capacity between 5,5 kg and 7 kg were the most important market segment in 10 EU countries (AT, BE, DE, ES, FR, GB, IT, NL, PT, SE) (BERTOLDI *et al.*, 2012). In 2012, the top selling appliances were those with a 7 kg rated capacity (Henkel, private communication).

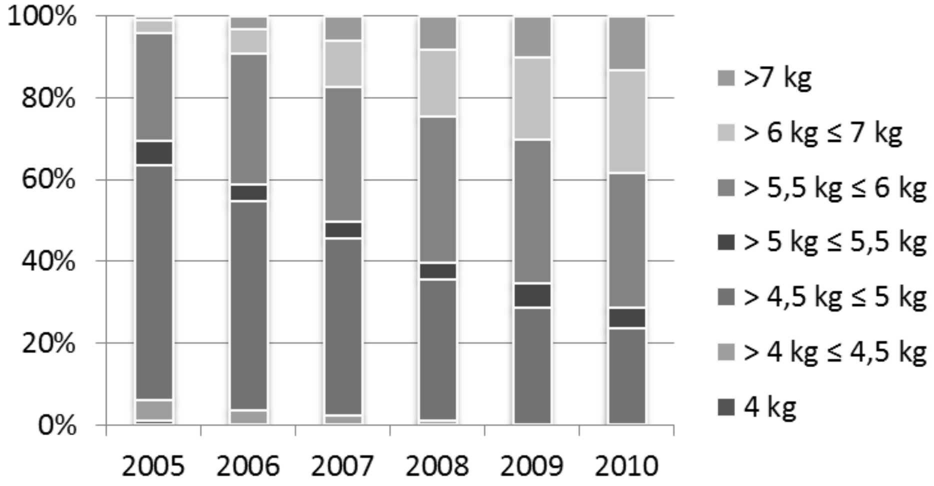

Figure 1-4: Average load capacity trends of household washing machines
(Data source: GfK cited from BERTOLDI *et al.*, 2012, own representation)

1.2.4 Resource consumption for washing purposes

1.2.4.1 Electricity consumption

The residential sector accounts for 29,71 % of total electricity used, the second largest electricity consumption sector. Within the residential sector, 7,2 % of electricity is consumed for laundry care. This shows the importance of washing and drying in the total electricity consumption. (BERTOLDI *et al.*, 2012)

The Eco-design preparatory study estimated the energy consumption of the washing machine stock in 2005 to be around 51 TWh / year, with an average yearly consumption per appliance of 295 kWh in the EU-27 households. (PRESUTTO *et al*, 2007)

A very comprehensive study regarding the energy consumption for washing purposes worldwide is delivered by PAKULA AND STAMMINGER, 2010. With their study, they covered roughly 780 million washing machines in about 2.3 billion households, which is about one third of the world population. PAKULA AND STAMMINGER note that most countries outside of their investigation still do their laundry washing by hand. According to their calculated estimation, the global electricity consumption of washing machines may be, at maximum, about 100 TWh /year of electricity. (PAKULA and STAMMINGER, 2010)

1.2.4.2 Water consumption

Total water abstraction in the European Union (EU 27) amounts to about 247 000 million m^3/year. On average, 44 % of total water abstraction in European Union is used for energy production, 24 % for agriculture, 17 % for public water supply and 15 % for industry (DWORAK *et al.*, 2007).

The Organization for Economic Co-operation and Development estimates that the share of the household in the total water consumption amounts to ca. 10 % to 30 % (OECD, 2013). Average consumption in OECD countries is about 100 000 l/year and person equals 174 liters per person per day. According to the European Environmental Agency, the average water consumption in Europe is between 100 liters and 320 liters, with an average of 155 liters per person and day (EEA, 2005).

Pakula and Stamminger estimate that 20 000 000 000 m^3 water is consumed worldwide for laundry washing in a washing machine (PAKULA and STAMMINGER, 2010).

1.2.5 Consumer behavior in use of washing machines

When taking into account the cradle-to-grave life cycle of a washing machine, i.e. including the production, use and disposal phase, it becomes obvious that the use phase is the most resource-consuming and waste-producing (Figure 1-5).

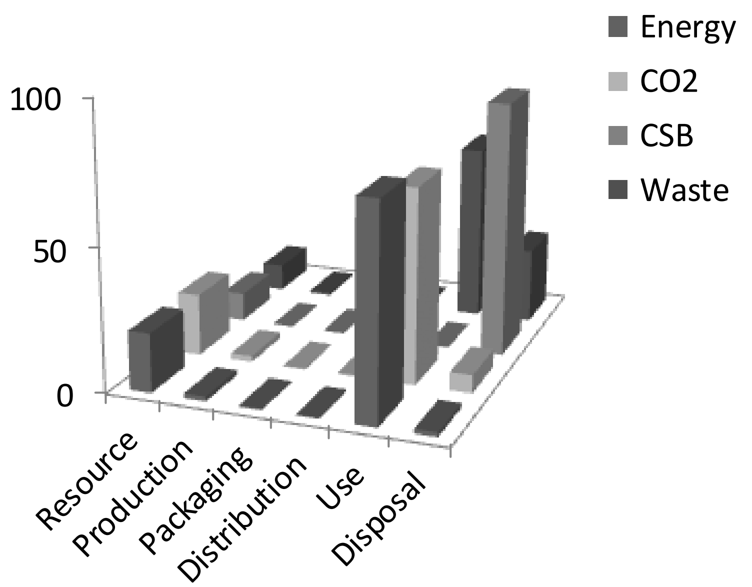

Figure 1-5: Life cycle analysis of a washing machine (Source: RÜDENAUER *et al.*)

Since washing machines are operated on consumer demand, their consumption of water, energy and detergents for a washing cycle is determined mainly by consumer-driven factors such as the frequency of washing, loading behavior, selection of the washing temperature/program and dosing of detergents (STAMMINGER *et al.*, 2008).

Much research regarding the behavior of the consumer when washing laundry has been conducted in the past years. However, much of this research was conducted by producers of the detergent and appliance industry, and hence was partially published or not published at all.

The most relevant studies of the European consumer washing behavior that have been published in the past 10 years are listed below.

2003 ARILD *et al.* conducted a survey with 4010 participants from Greece, the Netherlands, Norway and Spain with the goal of finding out how the consumers handle the washing of laundry (ARILD *et al.*, 2003).

JÄRVI *and* PALOVIITA conducted interviews in 2004 and 2005 with 340, in this case 299, people in Finland with the goal of finding out how consumers read/understand/implement the information and instructions on detergent (JÄRVI AND PALOVIITA, 2007).

In 2007, the University of Bonn conducted an online survey as part of a Preparatory Study for Eco-design Requirements of Energy-using Products. A total of 2500 participants from 10 European countries took part in the survey (PRESUTTO *et al*, 2007).

In 2007 BERKHOLZ *et al*. conducted a non-representative study on behalf of the German Federal Ministry of Economics and Technology and studied the washing behavior of 100 German households over a period of one month. The participants of the study were actually measuring the amount of laundry, detergent and electricity consumed for washing purposes. (BERKHOLZ *et al*., 2007)

STAMMINGER and GOERDELER published results of a survey conducted in 2005 with 3750 participants from all parts of Germany regarding their behavior in laundry washing. (STAMMINGER and GOERDELER, 2007)

In 2008 and 2011, the international association for soaps, care and cleaning products (AISE) conducted a survey with 5060 consumers in 23 European countries with an aim to find out laundry washing behavior. (AISE, 2008; AISE, 2011)

Not all studies have had the same research question; therefore the results of different studies cannot always be compared. However, the following data regarding the washing frequency, loading behavior and washing temperature selection is available.

1.2.5.1 Washing frequency

The number of washing cycles depends on factors such as the washing machine’s rated capacity or household size, loading behavior, etc. In the literature, information regarding the consumers' behavior when using washing machines is sometimes contradictory.

According to RÜDENAUER and GRIEßHAMMER, 164 wash cycles per year for an average household is conducted in Germany, Austria, and Switzerland. RÜDENAUER and GRIEßHAMMER list that the average number of washing cycles starts with 111 wash cycles for a one-person household and increases to 211 wash cycles per year for a four-person household (RÜDENAUER and GRIEßHAMMER, 2004)

STAMMINGER and GOERDELER published 4,5 washes per week (234 per year) as an average household number of washing cycles in Germany. Those figures are based on online questionnaires of more than 2000 persons. (STAMMINGER and GOERDELER, 2007)

PRESUTTO *et al*, state that the average washing frequency is 2,6 times per week for single- and 6,2 for four-person households. On average, 4,9 wash cycles per household per week, which equals on average 254 per year, are conducted. (PRESUTTO *et al*, 2007)

1.2.5.2 Loading of the washing machine

Many studies show that consumers do not fully use the rated capacity of their washing machine. BERKHOLZ *et al.* measured that, for example in Germany, the average load of a washing machine is 3,2 kg per wash cycle (BERKHOLZ *et al.*, 2007).

According to PRESUTTO *et al.*, most consumers claim to use the full loading capacity of their washing machine, but this does not mean that the rated capacity is really used (PRESUTTO *et al*, 2007).

DE ALMEIDA *et al.* state that the vast majority of the households always use the washing machine at over 75 % of its capacity. (DE ALMEIDA *et al.*, 2006)

Another measurement study shows that for an average washing machine capacity of 5 kg, consumers consider an average load of 3,7 kg to be a full load (KRUSCHWITZ *et al.*, 2014).

1.2.5.3 Use of washing temperature and program

According to Presutto *et al.*, the average nominal washing temperature in Europe is 45,8 °C. The most used program is the 40 °C program (37 %), the second most used temperature is 60 °C, which is 23 % of all the washes (Presutto *et al.*, 2007).

AISE publication also states that the 40 °C program is the most used program with 40 % of all the washes (AISE, 2013).

According to Stamminger and Goerdeler, the average washing temperature in Germany is 46,3 °C. The most used washing temperature is 40 °C with 37 % of all wash cycles. The second and third most used washing temperatures are 60 °C with 30 % of all washing cycles resp. 30 °C with 27 % of all washing cycles. (Stamminger and Goerdeler, 2007)

1.3 Sustainability

For weighing the climatic impact of emission of different greenhouse gases, the Intergovernmental Panel on Climate Change (IPCC) has, since its first assessment in 1990, used the Global Warming Potential (GWP). (Change, 1990)

The GWP has been subjected to much criticism because of its formulation, but nevertheless it has retained some favor because of the simplicity of its design and application, and also its transparency compared to proposed alternatives. (Shine *et al.*, 2005)

In December 1997, the *Kyoto Protocol* was adopted (Breidenich *et al.*, 1998). It entered into force on 16 February 2005 and for the first time it establishes legally binding limits for 37 industrialized countries on emissions of carbon dioxide and other greenhouse gases. (KyotoProtocol, 2013)

Kyoto Protocol set a binding reduction target for EU-15 GHG emissions of 8 % on average for the 2008–2012 period, compared with 1990 levels. In February 2011, the European Council reconfirmed the EU objective of reducing greenhouse gas (GHG) emissions by 80–95 % by 2050, as compared to levels in 1990 (Commission, 2011).

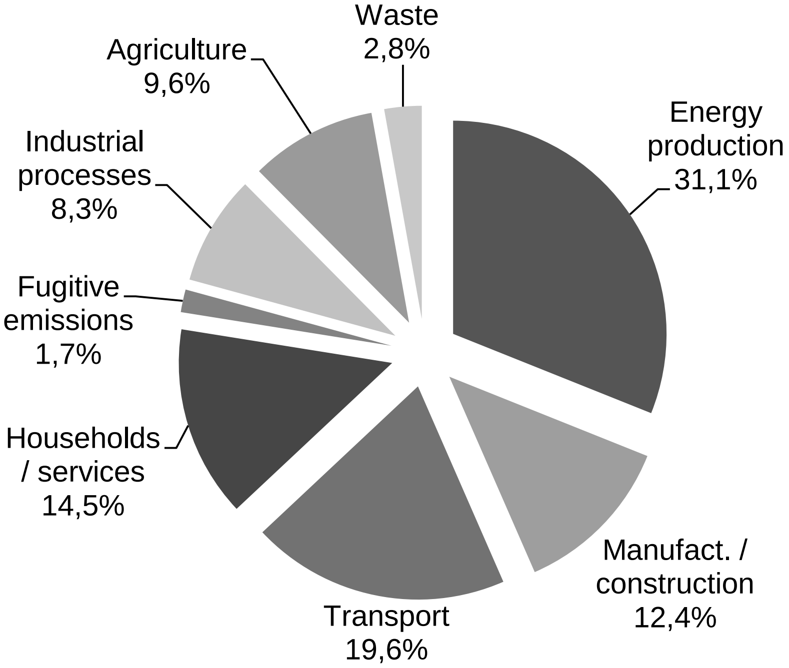

Figure 1-6: Contribution of the different sectors to the GHG emission (Source: EEA, 2010)

The contribution of the household and services to the global GHG emission is 14,5% (EEA, 2010). The EU objective of reducing greenhouse gas emissions can only be achieved when all the sectors contributing to the GHG emission contribute to that goal. By lowering the energy consumption, a total GHG emission can be achieved.

1.4 Demographic trends

According to the convergence scenario of EUROPOP2010, the EU-27’s population is projected to increase to 525 million by 2035, peaking at 526 million around 2040, and thereafter gradually declining to 517 million by 2060 (EUROSTAT, 2013) .

Not only is an increase of the population expected, but the number of households with a fewer number of household members is also increasing.

According to a study published by OECD by 2025-2030, one-person households will make up around 40 % or more of all households in the following European countries: Austria, France, Germany, the Netherlands, Norway, Switzerland and England. The authors of the study see the reason for this largely as a consequence of an ageing population, increase of the sole-parent household and current fertility rates and increases in life expectancy. (OECD, 2011)

1.5 Modeling approaches

There are different approaches to model the washing machines and their processes. Since the modeling of the washing machine is mainly done in the industry, the published research in this field is scarce. However, a selection of different modeling approaches is presented.

Parametrical modeling was used by WARD. In this research, the trajectory of a single concentrated mass was parametrically modeled in order to estimate the pressure drops that would occur on the mass as it is lifted by the baffles of the rotating washing machine drum and then subsequently dropped and impacted upon landing. (WARD, 2000)

TERPSTRA conducted research with an aim to evaluate whether the cleaning performance of domestic washing machines can be assessed with test soils by using the statistical modeling of the real experimentally-generated data. (TERPSTRA, 2001)

In 2003, PARK and WASSGREN conducted a computational simulation of textile dynamics inside a rotating drum. They used a simplified discrete element computational model to model the movement of the textiles. The textiles were modeled as spherical bundles, and their movement and interactions were modeled on the basis of the macroscopic behavior of these spherical textile bundles. (PARK and WASSGREN, 2003)

LAZAREVIĆ and VASIĆ used a mathematical modeling approach to model washing machines, where it is seen as a conglomerate of rigid multi-body systems. The basic properties of the washing machine are the basis for the construction of the model. (LAZAREVIĆ and VASIĆ, 2008)

RAMASUBRAMANIAN and TIRUTHANI used computational modeling to develop firstly a simplified 2D model, and then later a 3D model of a washing machine. The goal of the research was, by using the computer model, to develop a better understanding of the dynamics of modern washing machines that use balance rings. (RAMASUBRAMANIAN and TIRUTHANI, 2009)

MAC NAMARA *et al.* used the Positron Emission Particle Tracking (PEPT) technique, where radioactively labeled particles are monitored. In the research, a single tracer particle attached to a textile was monitored as it rotated and tumbled amongst other textiles in a commercially available domestic washing machine. The aim of the research was to understand the mechanisms by which mechanical action is imparted onto wet textiles during washing. (MAC NAMARA *et al.*, 2012)

IN 2005, RÜDENAUER *et al.* conducted a life cycle assessment for washing machines to model the complex interaction between a product and the environment. The model includes the life cycle of a product from the production, use and disposal phases. In the study, RÜDENAUER *et al.* compare the acquisition and use of a washing machine with a larger rated capacity to the acquisition and use of a washing machine with a rated capacity of 5 kg under environmental and economic aspects. (RÜDENAUER *et al.*, 2005)

The presented modeling approaches focus on a specific aspect of a washing machine (e.g. exploring the influence of mechanics in a washing process), but none of the models depicts the whole washing process. Furthermore, those models also do not include the washing machine’s rated capacity, except that of RÜDENAUER *et al*. Finally, the role of the consumer / household is either only rudimentary or not included in those models at all.

2 Objective

On the European market at present, two opposing trends can be observed. On one hand, an increase of the average load size of the washing machines that are sold on the market is observed. On the other hand, the demographic structure of the European households is changing, resulting in a decrease of the average household size and hence results in a reduced amount of laundry to be washed.

In addition to those two opposing trends, it should be kept in mind that consumers at present do not fully use the rated capacity of their washing machines, and consider a partial load level as a full load.

Those considerations lead to the question: “What kind of washing behavior is needed, so that the usage of washing machines with a higher rated capacity has a low impact on the environment?”

In order to answer that question, the following needs to be done:

- Firstly, a model of a virtual washing machine that is based on average and typical data of washing machines available on the market shall be developed. The virtual washing machine should be flexible, so that the input parameters selected by the consumer can be varied.
- Secondly, a virtual washing household that incorporates various washing behavioral parameters shall be developed.
- Thirdly, a simulation of the usage of the virtual washing machine by the virtual washing households shall be developed. By conducting parallel simulations and by varying device-, household-, and behavioral parameters, optimal parameter combinations with low environmental impact shall be determined and hence conclusions regarding an optimal consumer behavior are to be drawn.

3 Material and methods

All material and methods used for testing the washing machines are based on the experimental setup required in EN60456:2005.

The framework of EN60456:2005 is broadened and tests with a load of 25 % and 75 % as well as tests with detergent under- and overdose are included. Those cases are marked accordingly. In some cases, the EN60456:2010 is applied and also those cases are marked accordingly.

3.1 Material

3.1.1 Tested washing machines

All tested washing machines are front loading washing machines and are prepared in accordance with the manufacturer's specified safety instructions and installed in accordance with EN60456:2005.

Table 3-1: List of tested washing machines

Manufacturer and washing machine model	rated capacity	Ident. Nr:
Miele Novotronic W1514	5 kg	WM1
Indesit IWB 5125	5 kg	WM2
BOSCH Maxx6 Eco Wash WAE2834P	6 kg	WM3
Bauknecht WA UNIQ 714FLD	7 kg	WM4
AEG Öko Lavamat 76850 A	7 kg	WM5
BOSCH Logixx8 Vario Perfekt WAS32792	8 kg	WM6
Haier HW-F1481	8 kg	WM7
Indesit PWE 8168W	8 kg	WM8
Bauknecht WAB-1210	11 kg	WM9

3.1.2 Washing machine used for standardization and neutralization

MIELE W1514 NOVOTRONIC and WASCATOR CLS are used for the normalization process of the test load. MIELE NOVOTRONIC W1514 program software is modified so that it complies with the standard procedure as described in EN60456:2005.

Table 3-2: Equipment used for the normalization process of the load

Washing machine	washing machines tested
W1514 Novotronic	WM1, WM3, WM4, WM5, WM6
Wascator	WM2, WM7, WM8, WM9

3.1.3 Test load

The test load consists of the base load and the soil strips as specified. Base load is used in accordance with EN60456:2005 and consists of cotton bed sheets, cotton pillowcases, and cotton towels. Soiled test trips are in accordance with EN60456:2010 and were manufactured by “EMPA Testmaterialien”.

Table 3-3: Soil strips and respective batch number used for the tests

EMPA Batch number	**Washing machines tested**
Batch 21	WM1, WM3, WM4, WM6
Batch 27	WM5
Batch 35	WM2, WM7, WM8
Batch 45	WM9

3.1.4 Detergent

Reference detergent A* is used in the test as specified by the EN50456:2005. During the testing time, all three components are stored separately and used within the expiry date as stated in the documentation provided by the manufacturer.

Table 3-4: Detergent

	Component batch Nr.		
Washing machines tested	**base powder**	**sodium perborate tetrahydrate**	**bleach activator (TAED)**
WM1, WM3, WM5, WM6	167-513	237-394	24704603
WM2, WM4, WM7, WM8, WM9	237-970	287-984	26746203

3.1.5 Software

Table 3-5 lists all software used.

Table 3-5: Overview of software used

Software name	Used for
Matlab 2010a	Simulation of a washing process
IBM SPSS Statistics 21	Multivariate statistics i.e. Multiple linear regression
Colorimeter software	Evaluation of the EMPA soil strips
Alborn	Data logger software used to monitor and record the test experiment

3.2 Methods

3.2.1 Washing machines tests

The framework of EN60456:2005 is extended so that some test parameters such as temperature, detergent dosage and load size are varied.

In addition, differing from EN60456:2005 in which five repetitions of each parameter setting are required, in this case one repetition is conducted for each parameter setting.

3.2.1.1 Load

The load is varied so that tests with 25 %, 50 %, 75 % and 100 % of the rated washing machine load capacity were conducted. Furthermore, tests with no load were performed in order to simulate a very small load. Table 3-6 shows the loading scenarios for different washing machines.

Table 3-6: Loading scenarios for different washing machines' rated capacities

WM rated capacity	Load size 25 % in kg	Load size 50 % in kg	Load size 75 % in kg	Load size 100 % in kg
5 kg	1,25	2,5	3,75	5
6 kg	1,5	3	4,5	6
7 kg	1,75	3,5	5,25	7
8 kg	2	4	6	8
11 kg	2,75	5,5	8,25	11

3.2.1.2 Detergent dosing

In order to reflect a more consumer-relevant behavior in the testing procedure, the amount of the nominal dose of detergent was calculated as specified in EN60456:2010.

Nominal dosing: $40g + 12\ g\ /\ kg\ laundry$

To simulate the over- and under-dosing, the following dosages are included.

Overdosing: $\frac{3}{2} \times (40\ g + 12\ g\ /\ kg\ laundry)$

Under dosing: $\frac{1}{2} \times (40\ g + 12\ g\ /\ kg\ laundry)$

Prior to the dosing the detergent, the detergent dispenser is cleaned and dried.

3.2.1.3 Temperature/program

The washing temperature is varied so that the washing program at 30 °C, 40 °C, and 60 °C are conducted. Combining all varied parameters results in a total of 39 tests conducted for one single washing machine. Washing program is “cotton” and the spin speed is 1400 rpm. During the washing cycle the water temperature in the sump is monitored by a sensor placed in the space between the inner and outer drum at the bottom of the washing machine’s drum.

Table 3-7: Test design and variation of the parameters

Load size	**Temperature**			**Number of tests**
	30 °C	**40 °C**	**60 °C**	
0 %	No detergent	No detergent	No detergent	3
25 %	Over dose Nominal dose Under dose	Over dose Nominal dose Under dose	Over dose Nominal dose Under dose	9
50 %	Over dose Nominal dose Under dose	Over dose Nominal dose Under dose	Over dose Nominal dose Under dose	9
75 %	Over dose Nominal dose Under-dose	Over dose Nominal dose Under dose	Over dose Nominal dose Under dose	9
100 %	Over dose Nominal dose Under dose	Over dose Nominal dose Under dose	Over dose Nominal dose Under dose	9

The experimental setup is based on the following recurring test scheme based on EN60456:2005 (Figure 3-1).

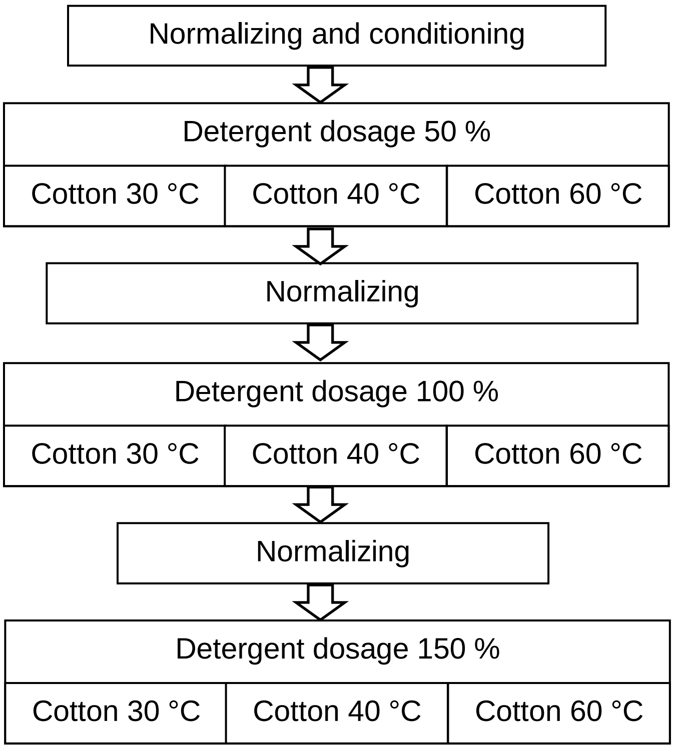

Figure 3-1: Example of a testing procedure on an example of a 25 % load

3.2.1.4 Normalization and conditioning

In accordance with the EN60456:2005, the normalization process is conducted in batches of 3,75 kg. If the quantity exceeded the quantity of 3,75 kg, the laundry amount is divided into smaller load sizes.

Conditioning is conducted as described in EN60456:2005. The individual items of laundry are left for 24 hours on a rack. All items are separately hung on, so that a circulation of the air is ensured.

3.2.1.5 Reproduction tests

Every constellation of the parameters is tested once. In order to test the reproducibility of the results, every washing machine is tested in so-called reproduction tests. For this reason, three tests in accordance with EN60456:2005 with a full load, using the washing program "cotton 60 °C", and with a detergent dosage of 100 % are conducted.

3.2.1.6 Evaluation of the soil strips

Upon completion of a test, the test load is removed no later than ten minutes after the completion of the washing process. The attached soil strips are separated. Test loads without the soil strips is then weighted and dried. The separated soil strips are air-dried, ironed, and evaluated by measuring the tristimulus Y reflectance in accordance with EN60456:2005.

3.2.1.7 Calculation the washing performance index

According to the standard EN60456:2005, the CIE Y values calculated for every washing machines test is set in proportion to those of a reference washing machine.

In EN60456:2005, the reference washing machines tests are conducted by washing 5 kg of laundry in a reference washing machine and using 180 g of the reference detergent.

In EN60456:2010, the reference washing machine tests are conducted the same as in EN60456:2005, except that the detergent dosage is 110 g.

In this research, the reference washing machine tests are not conducted. Instead, the documentation provided by the soil strip producer “Empa Testmaterialien” is used.

The values in the documentation are provided only in accordance with EN60456:2005 for 180 g and 135 g. Based on those values, the CIE Y values for 110 g are extrapolated.

Table 3-8: CIE Y values of different batches and extrapolated values for 110g of detergent

Batch Number	CIE Y values for 180 g	CIE Y values for 135 g	Extrapolated Y CIE values for 110g
21	355,1	345,7	340,5
27	353,6	342,9	337,0
35	353,5	340,7	333,6
45	348,7	336,1	329,1

3.2.1.8 Testing conditions

All testing conditions are maintained as defined in EN60456:2005

Table 3-9: Testing conditions in accordance with EN60456:2005

Parameter	Interval
Ambient temperature	23 ± 2 °C
Water temperature	15 ± 2 °C
Water pressure	2,4 ± 0,5 bar
Water hardness	2,5 ± 0,2 mmol / L
Power supply voltage	230 V ± 1 %
Power supply frequency	50 Hz ± 1 %

3.2.2 Construction of the model of a virtual washing machine

During the washing machine tests, input parameters (independent variables) are: washing temperature, load size, washing machine’s rated capacity, duration of the main wash and amount of detergent. The output parameters (dependent variables) are: Energy consumption, water consumption, washing performance and washing time.

By using this data, a model of a virtual washing machine is constructed. This model consists of a set of multiple linear regression equations that puts into relation the input and output parameters, and hence can be used to predict the amount of resources consumed during a single washing cycle (detergent, water and energy).

The basis for the construction of the virtual washing machine model is a general equation for multiple linear regressions.

$$Y = B_0 + B_1 * X_1 + B_2 * X_2 + \ldots + B_n * \mathrm{X}_n \qquad (3\text{-}1)$$

Where is:

$Y = dependent\ variable$

$X_1,\ X_{2,} X_n = independent\ variables$

$B_0, B_1, B_2,\ B_n = \ B\ parameters\ associated\ with\ independent\ variable$

Based on the eq. (3-1) and the input parameters, three different multiple regression equations are developed. Each of the equations is used to predict one of the consumed resources (i.e. amount of the detergent, water and energy consumed for a single washing cycle).

3.2.2.1 Calculations of the consumption in CO_2 equivalents

In order to be able to compare different resources (water, detergent and energy), its respective amounts are converted into the CO_2 equivalents by using the conversion values as presented in Table 3-10.

Table 3-10: Overview of CO2 conversion factors

Factor	**Gram CO_2 per unit**	**Unit**
CO_2WATER[1]	6,16	liter
CO_2ENERGY[2]	601	kWh
CO_2DETERGENT[3]	1,7	gram

For the calculation of CO_2 equivalents for detergent consumed during a single washing cycle ($COE_{detergent}$), the following equation is used:

---

[1] Source: Jungbluth, N., des Gas, S. V. & Wasserfaches, S. (2006) Vergleich der Umweltbelastungen von

[2] Source: Icha, P. (2013) Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2012. *Climate Change, Umweltbundesamt,* **07/2013**.

[3] Source: Henkel, private communication

$$COE_{detergent} = \mathrm{X_{DETERGENT}} * \mathrm{CO_2DETERGENT} \tag{3-2}$$

Where is:

$\mathrm{X_{DETERGENT}} = amount\ of\ detergent\ consumed\ during\ a\ single\ washing\ cycle$

For the calculation of CO_2 equivalents for water consumed during a single washing cycle (COE_{water}), the following equation is used:

$$COE_{water} = \mathrm{X_{WATER}} * \mathrm{CO_2WATER} \tag{3-3}$$

Where is:

$X_{WATER} = amount\ of\ detergent\ consumed\ during\ a\ single\ washing\ cycle$

For the calculation of CO_2 equivalents for energy consumed during a single washing cycle (COE_{energy}), the following equation is used:

$$COE_{energy} = \mathrm{X_{ENERGY}} * \mathrm{CO_2ENERGY} \tag{3-4}$$

Where is:

$\mathrm{X_{ENERGY}} = \mathrm{amount\ of\ detergent\ consumed\ during\ a\ single\ washing\ cycle}$

For the calculation of total CO_2 equivalents consumed during a single washing cycle (COE_{TOTAL}), the following equation is used:

$$COE_{TOTAL} = COE_{detergent} + COE_{water} + COE_{energy} \tag{3-5}$$

The following figure shows a schematic of the model construction

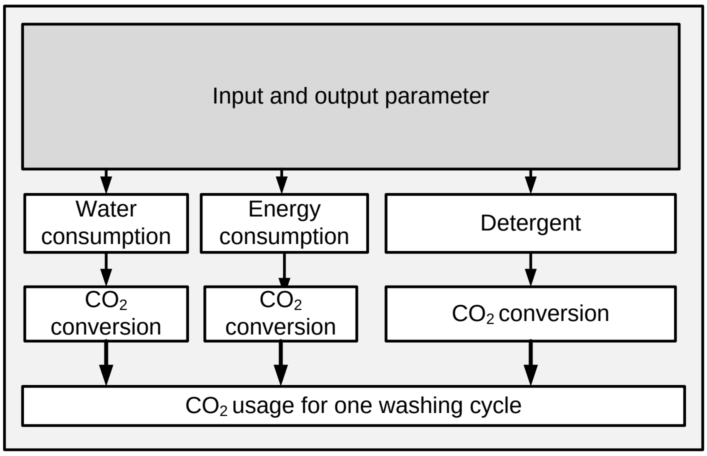

Figure 3-2: Schematic of the mathematical model construction of a washing machine (own representation)

3.2.3 Construction of the model of virtual washing household

In order to simulate the usage of the virtual washing machine, the following concept of virtual washing household is presented.

It is assumed that the usage of the washing machine is defined by:

1. Washing machine related factors (washing machine's rated capacity and duration of the washing programs)
2. Household related factors, such as the household size, amount and type of laundry that has to be washed per person and week.
3. Washing behavior related factors (e.g. washing temperature, loading behavior and dosing behavior)

Simulation of a routine structure as an example for a washing of laundry that has to be washed in a 30 °C program is presented in Figure 3-3. Analogously, the simulation structure can be applied to a 40 °C and 60 °C washing program.

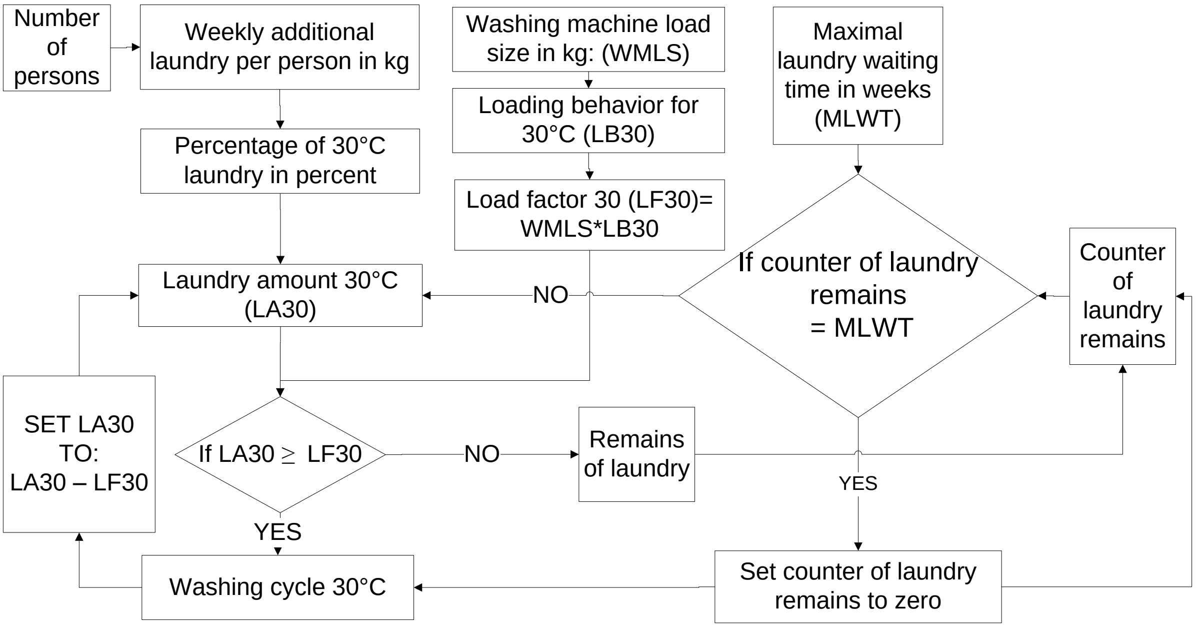

Figure 3-3: Example of a schematic of the simulation

Simplified, the simulation can be described by the following five steps:

1) Parameter induction
    a. Setting of the washing machine's rated capacity
    b. Setting of the number of persons in household
    c. Setting the amount of laundry that has to be washed per person and per week.
    d. Setting of the maximal laundry waiting time (MLWT)
    e. Set the week counter to zero
2) Calculation prior to wash
    a. Determine the amount of *rest load* from previous week. In the first week this value is zero.
    b. Calculation of the *washing cycle load amount* by multiplying the washing machine's rated capacity with the loading factor.
    c. Calculation of the *available amount of laundry that has to be washed*
3) Washing process simulation

   a. If the *available amount of laundry* that has to be washed is lower than *washing cycle load amount,* continue to (4).
   b. If the *available amount of laundry* that has to be washed is equal to or higher than *washing cycle load amount,* conduct the washing simulation. Repeat this step until the *available amount of laundry* is lower than the *washing cycle load amount.* The remaining amount of laundry is added to the next week's amount of laundry.

4) Add one week to the week counter.
5) Check whether the duration of the simulation has been reached – if not, restart from Step (2).
6) If yes →, end of the simulation.

With every week, the new amount of laundry per person is introduced into the simulation.

3.2.4 Combination of virtual washing household and virtual washing machine

Simulation of long-term usage is conducted by combining the model of the virtual washing household and the model of the virtual washing machine.

By using Matlab software, a program that combines those two segments is programmed so that the following input parameters can be varied:

- Washing machine's rated capacity
- Number of persons in household
- Amount of laundry per person
- Type of laundry per person
- Maximal laundry waiting time
- Loading behavior for certain types of laundry
- Duration of the simulation

3.2.4.1 Correction of the detergent amount

It is to be expected that in some cases, when a small load is washed in a washing machine with a high rated capacity, the calculated amount of detergent is very low. However, consumers always dose a certain amount of detergent. In order to include this consumer behavior in the model, the following convention is implemented in the yearly simulation:

When the amount of calculated detergent for a single wash is lower than 40 g (EN60456:2010 base amount of detergent), the calculated amount of detergent is automatically corrected to 40 g.

3.2.4.2 Scenario used for simulation

The simulations are conducted by using the following general simulations parameters:

Duration of the simulation = 52 weeks

Weekly additional laundry = 4 kg per person

The average composition of the load (KRUSCHWITZ *et al.*, 2014)

Washing load at 30 °C = 23 % of total load
Washing load at 40 °C = 46 % of total load
Washing load at 60 °C = 31 % of total load

The maximal loading factor for:

30 °C washing cycle = 50 % of the rated capacity
40 °C washing cycle = 70 % of the rated capacity
60 °C washing cycle = 90 % of the rated capacity

3.2.5 Average values calculations

For the calculation of the average values, the following formula was used:

$$\bar{x}_{arithm} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3-6}$$

Where is:

$\bar{x}_{arithm} = arithmetic\ mean$
$x = observed\ values$
$n = number\ of\ observations$

4 Results

In this chapter, all data received by the experiments, mathematical modeling, and simulations are worked out and presented.

4.1 Results of the washing machines tests

An overview of the data of the washing machines tests is presented.

4.1.1 Water consumption

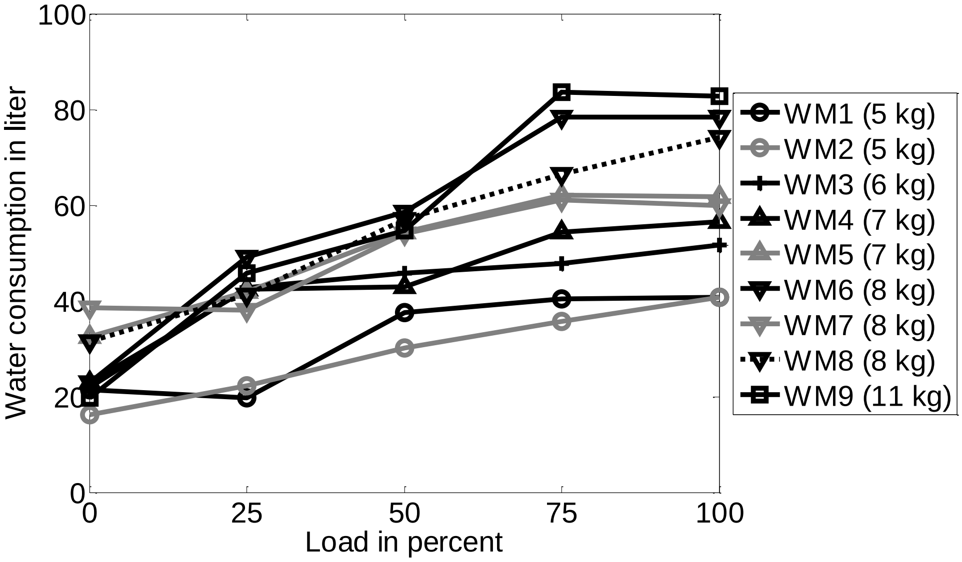

Figure 4-1: Water consumption versus load of nine washing machines - washing temperature is 60 °C

Water consumption increases with an increase of the load size for all washing machines tested (Figure 4-1). Comparison of slopes indicates that washing machines differ in their ability to adapt its water consumption to the amount of load. The slope of the WM3 shows that the load size has the lowest influence on water consumption. Other washing machines have quantity controls that are more sensitive to a variation of the load.

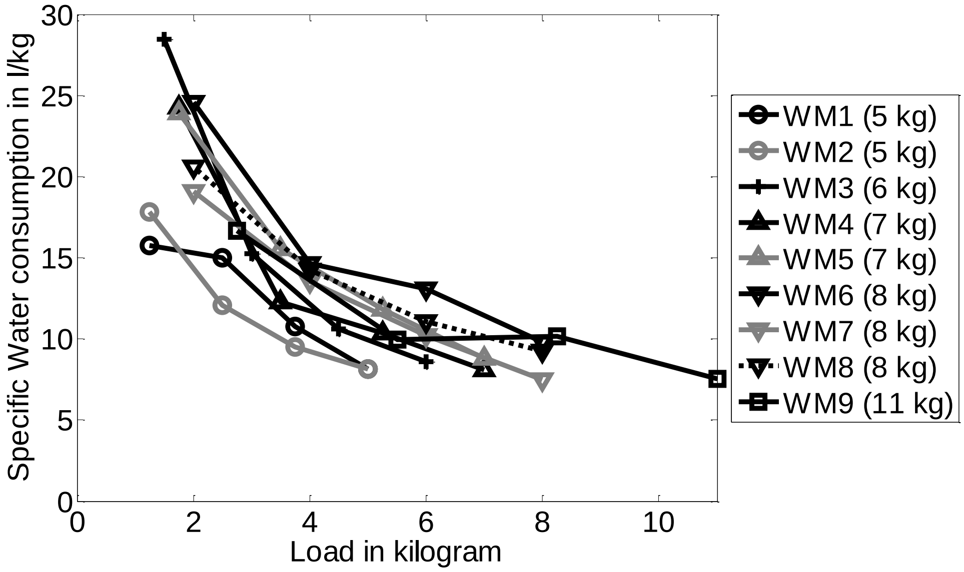

Figure 4-2: Comparison between the specific water consumption and the load size

With an increase of the load, specific water consumption decreases. Variations in specific water consumption are lowest when the washing machine is fully loaded, and highest when the washing machine is loaded with 25 % of the rated capacity. When washing machines are underloaded, the differences in specific water consumption for washing nearly same amount of load vary to up to twice (Figure 4-2).

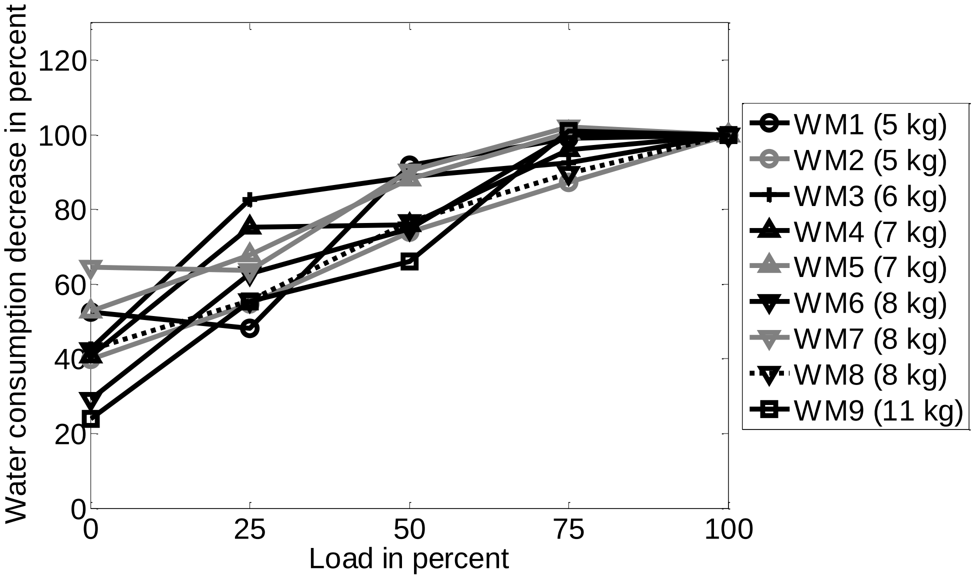

Figure 4-3: Water consumption versus load amount - washing temperature is 60 °C

Setting the water consumption of a fully-loaded washing machine as 100 % reveals that water reduction is not proportional to the load reduction (Figure 4 3).

A load decrease of 50 % leads, in the best case, to a water consumption decrease of less than 40 % (in the worst case, the decrease is less than 5 %).

Table 4-1: Ratio between the main wash water consumption and the total water consumption (mean values), in dependence of the detergent dosage

	Detergent dose in percent of a nominal dose			
	50 %	100 %	150 %	Mean
WM1	1:3,4	1:3,4	1:3,3	1:3,4
WM2	1:3,3	1:3,3	1:3,3	1:3,3
WM3	1:4,0	1:3,9	1:3,7	1:3,9
WM4	1:4,0	1:4,0	1:4,0	1:4,0
WM5	1:3,5	1:3,5	1:3,6	1:3,5
WM6	1:4,1	1:4,1	1:4,1	1:4,1
WM7	1:3,4	1:3,3	1:3,3	1:3,3
WM8	1:3,2	1:3,1	1:3,2	1:3,2
WM9	1:3,3	1:3,3	1:3,3	1:3,3
Mean				1:3,5

Table 4-2: Ratio between the main wash water consumption and the total water consumption (mean values), in dependence of the load size

	Washing machine load in percent of rated capacity				
	25 %	50 %	75 %	100 %	Mean
WM1	1:3,0	1:3,4	1:3,5	1:3,6	1:3,4
WM2	1:3,8	1:3,4	1:3,1	1:2,9	1:3,3
WM3	1:4,8	1:4,0	1:3,4	1:3,3	1:3,9
WM4	1:3,8	1:3,8	1:3,8	1:4,5	1:4,0
WM5	1:3,5	1:3,9	1:3,4	1:3,3	1:3,5
WM6	1:4,3	1:4,2	1:3,9	1:3,9	1:4,1
WM7	1:3,6	1:3,5	1:3,2	1:3,0	1:3,3
WM8	1:3,5	1:3,3	1:3,0	1:2,9	1:3,2
WM9	1:3,4	1:3,3	1:3,2	1:3,2	1:3,3
Mean					1:3,5

The ratio values, in dependence of the load size, show the lowest mean values in the case of the washing machine WM8 (1:3,2) and the highest values in the case of the WM6. The mean ratio is 1:3,5.

4.1.2 Energy consumption

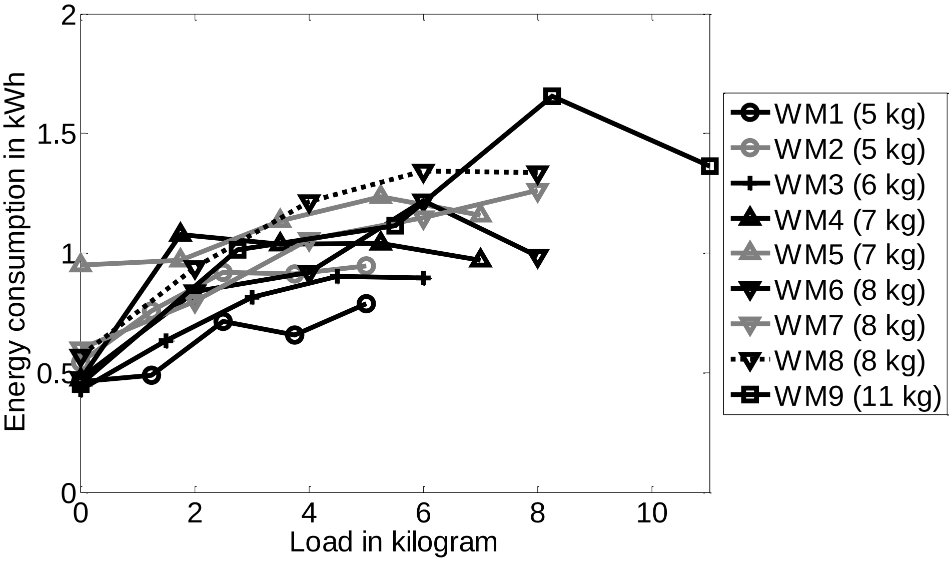

Figure 4-4: Energy consumption in kWh versus load size. Washing temperature 60 °C

Similar to the water consumption, the energy consumption increases with an increase of the load size. WM4 is an exception and consumes at the load level of 25 % more than when it is fully loaded (Figure 4-4).

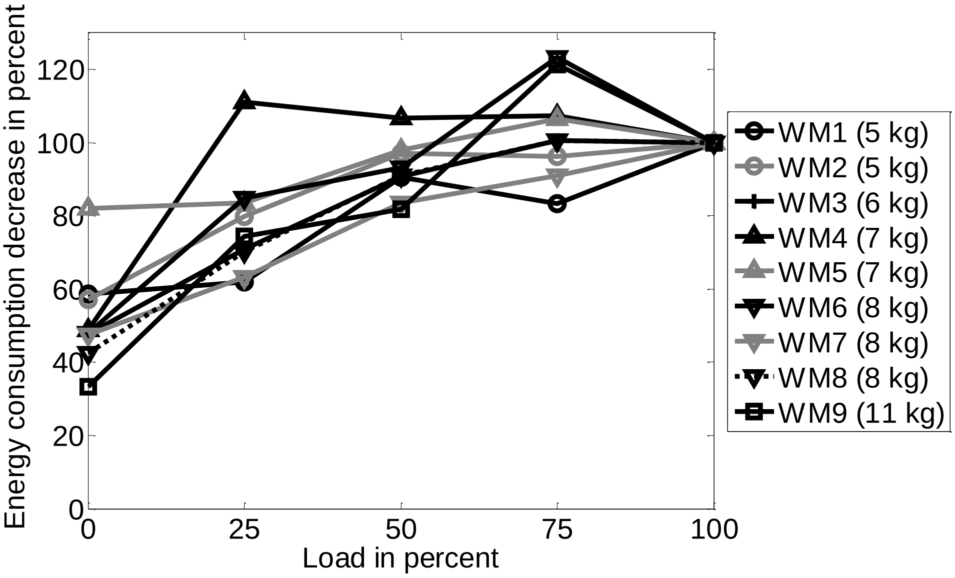

Figure 4-5: Energy consumption versus load amount - washing temperature is 60 °C

Setting the energy consumption of a fully loaded washing machine as 100 % reveals that energy reduction is not proportional to the load reduction. A decrease of the load by 50 % results in a decrease of energy consumption of maximally 20 %.

Furthermore, WM6 and WM9 consume 20 % more energy when underloaded (75 % or the rated capacity) than when fully loaded. WM4 consumes 10 % more energy when underloaded (25 % of the rated capacity) than when fully loaded.

4.1.3 Washing performance

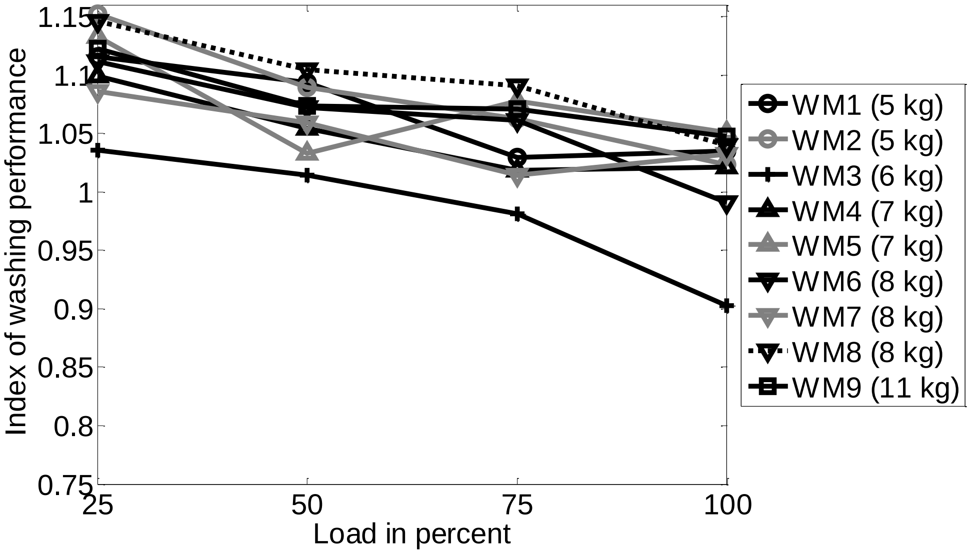

Figure 4-6: Index of washing performance versus load for cotton 60 °C

With an increase of the load size, the washing performance decreases. WM3 shows the lowest washing performance index values for all loading sizes (Figure 4-6).

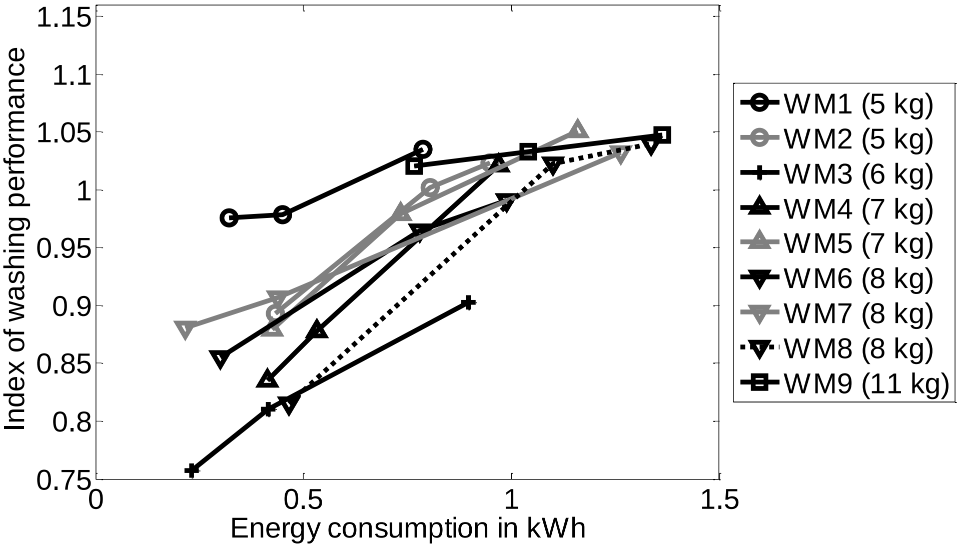

Figure 4-7: Index of washing performance vs. energy consumption. From left to right the energy values indicate the machines' energy use for 30 °C, 40 °C and 60 °C washing programs

With an increase of the washing temperature, the energy consumption and the washing performance increases. In the case of WM1, an increase of the washing temperature from 30 °C to 40 °C results in an increase of the energy consumption of 0.13 kWh and the washing performance increases 0,003 index points.

In the case of the WM8, an increase of the washing temperature from 30 °C to 40 °C results in an increase of the energy consumption of 0,63 kWh and a washing performance increase of 0,207 index points. An increase of the washing temperature from 40 °C to 60 °C results in an increase of the energy consumption of 0,24 kWh and an increase of the washing performance of 0,018 washing performance index points. (Figure 4-7).

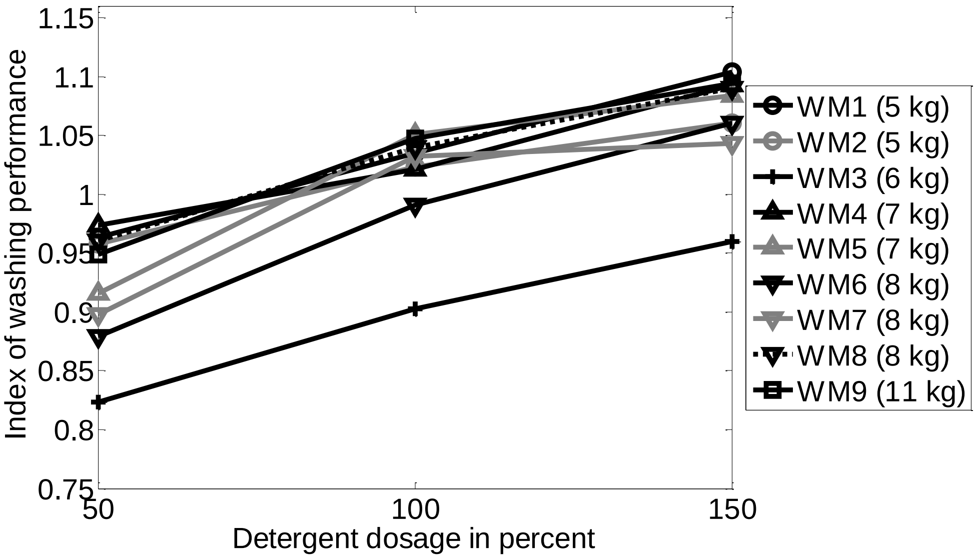

Figure 4-8: Index of washing performance vs. detergent dosage

Washing performance varies between different washing machines. An adjustment of the washing performance can also be done by varying the amount of the detergent. Comparison of the slopes shows a slightly higher loss in performance when the dosage is reduced from 100 % to 50 % than from 150 % to 100 % (Figure 4-8).

Table 4-3: Overview of average washing performance achieved at different washing temperatures

Washing temperature	Average washing performance at specific temperature	Washing performance setting in the simulation
30 °C	0,9288	0,93
40 °C	0,9984	1,00
60 °C	1,0449	1,04

4.1.4 Duration of the main wash

Comparison of average main washing duration data shows a large variety among different washing machines types and nominal washing temperatures. With an increase of the washing temperature, the duration of the main wash increases as well in most cases. The lowest values are reached by the washing machine WM3 at 30 °C (18 minutes) and the highest values are reached by WM9 at 60 °C (173 minutes).

Table 4-4: Overview of different average durations of the main wash at the following washing temperatures

	Duration of the main wash cycle in minutes at the following temperatures (average values)		
	30 °C	40 °C	60 °C
WM1	56	56	55
WM2	39	82	82
WM3	18	25	37
WM4	65	72	83
WM5	65	66	81
WM6	74	86	94
WM7	61	61	72
WM8	31	160	156
WM9	156	158	173

4.1.5 Washing temperature: nominal versus actual washing temperature

The washing temperature set on the washing machine (nominal washing temperature) and the washing temperature measured by the washing machines sensor (actual washing temperature) do not always match. In the case of the nominal temperature of 30 °C, the average actual temperature values range between 26 °C and 35 °C. In the case of a nominal temperature of 40 °C, the average actual temperature values range between 39 °C and 48 °C, and in the case of nominal temperature of 60 °C, the average actual temperatures range between 49 °C and 63 °C (Table 4-5).

Table 4-5: Overview of average actual washing temperatures that were achieved instead of the respective nominal temperature

Average actual washing temperatures in °C			
	30 °C	40 °C	60 °C
WM1	29	38	56
WM2	35	48	59
WM3	33	44	63
WM4	29	40	56
WM5	30	39	55
WM6	26	41	56
WM7	27	37	57
WM8	29	43	51
WM9	32	39	49

4.2 Construction of model of virtual washing machine

The virtual washing machine model consists of a set of equations, each used to calculate one of the resources consumed during a washing cycle (water, energy and detergent). Figure 4-9 shows a schematic (based on Figure 3-3) on how the virtual washing machine is constructed.

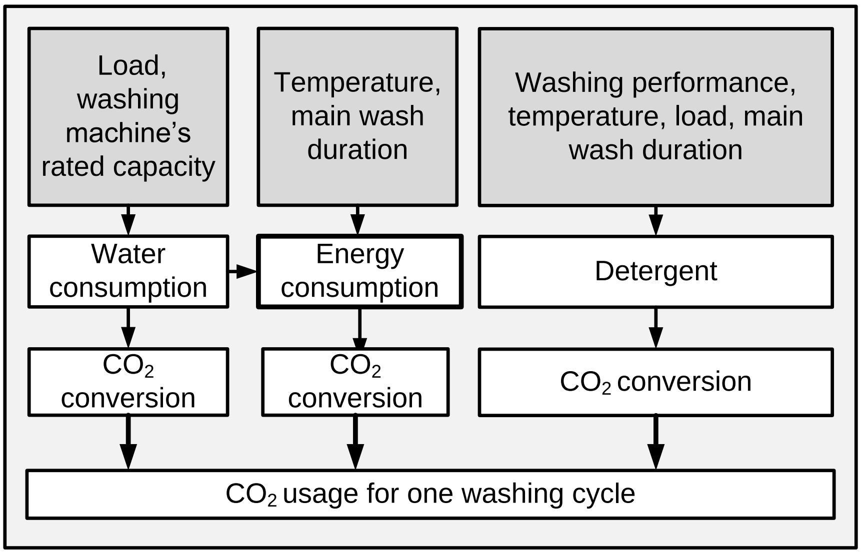

Figure 4-9: Schematic of a construction of a virtual washing machine based on the data received during the washing machine tests

4.2.1 Water consumption equation

Multiple linear regression analysis (Table 4-6) was used to develop a model for predicting water consumption from load size and rated capacity. The two-predictor model is able to account for 88 % of the variance in water consumption.

Table 4-6: Summary statistics, correlations, and results from the regression analysis (water consumption)

Variable	mean	std	correlation with WC	multiple regression weights	
				b	β
Water consumption (WC)	14,772	5,1606			
Load size (LS)	4,2	2,571	0,929***	1,725***	0,860
WM Rated capacity (WMRC)	7,2	1,77	0,527***	0,476***	0,162
Constant	4,116				
R = 0,940					
R^2 = 0,884					
$R^2_{Adjusted}$ = 0,883					
F = 1359,228***					

* p < 0,05 ** p < 0,01 ***p<0,001

Tests to see if the data met the assumption of collinearity indicated that multicollinearity is not a concern: Load size (Tolerance = 0,820, VIF = 1,220), rated capacity (Tolerance = 0,820, VIF = 1,220).

The histogram of standardized residuals indicated that the data contained approximately normally distributed errors, as did the normal P-P plot of standardized residuals, which showed points that were not completely on the line, but close. The scatterplot of standardized residuals showed that the data met the assumptions of homogeneity of variance and linearity.

The general regression equation (3-1), in combination with the variables selected by the multiple regression analysis, is used to construct a model. The final equation for predicting the water consumption during the main wash is:

$$\boldsymbol{CW_{mw} = 4,116 + 1,725 * \mathrm{LOAD} + 0,476 * WMV} \tag{4-1}$$

Where is:

$\mathrm{LOAD} = amount\ of\ laundry\ in\ kg$
$WMV = rated\ capacity\ in\ kg$
$CW_{mw} = water\ consumption\ during\ the\ main\ wash$

The ratio between the water consumed during the main wash to total water consumption is 1:3,5 (Table 4-1 and Table 4-2), so that the equation for calculation of the total amount of water consumed for a single washing cycle (CW_{TOTAL}) is the following:

$$\boldsymbol{CW_{TOTAL} = CW_{mw} * 3,5} \tag{4-2}$$

Combining the eq. (4-1) and the eq. (4-2) equation (4-3) results:

$$\boldsymbol{CW_{TOTAL} = 3,5 * (4,116 + 1,725 * \mathrm{LOAD} + 0,476 * WMV)} \tag{4-3}$$

4.2.2 Energy consumption equation

Analogous to the construction of the equation for calculating the water consumption, the equation for calculating energy consumption is constructed. Multiple linear regression analysis is used (Table 4-7) to develop a model for predicting energy consumption based on water consumption, washing temperature and the duration of the main wash. The three-predictor model is able to account for 92 % of the variance in energy consumption, *F* (3, 351) = 1323,465; *p* < 0,001.

Table 4-7: Summary statistics, correlations and results from the regression analysis (energy consumtion)

Variable	mean	std	correlation with WC	multiple regression weights b	β
Energy consumption (EC)	0,525	0,3157			
Water consumption (WC)	14,74	5,021	0,470***	0,02246***	0,357
Washing temperature (WT)	41,90	11,115	0,743***	0,02040***	0,720
Duration of main wash (DMW)	78,95	42,994	0,642***	0,00247***	0,337
Constant	-0,836				
R	0,959				
R^2	0,919				
$R^2_{Adjusted}$	0,918				

* p < 0,05 ** p < 0,01 ***p<0,001

Table 4-8: Correlations between predictor variables

	EC	WC	WT	DMW
Energy consumption (EC)				
Water consumption (WC)	0,470***			
Washing temperature (WT)	0,743***	-0,09*		
Duration of main wash (DMW)	0,642***	0,527***	0,162***	

* p < 0,05 ** p < 0,01 ***p<0,001

Tests to see if the data met the assumption of collinearity indicated that multicollinearity is not a concern: Water consumption in the main wash (Tolerance = 0,690, VIF = 1,449), washing temperature (Tolerance = 0,931, VIF = 1,074) duration of the main wash (Tolerance = 0,678, VIF = 1,476).

The histogram of standardized residuals indicated that the data contained approximately normally distributed errors, as did the normal P-P plot of standardized residuals, which showed points that were not completely on the line, but close. The scatterplot of standardized residuals showed that the data met the assumptions of homogeneity of variance and linearity.

Based on the results of the multiple regression analysis, the final equation to predict the energy consumption is constructed. The general regression equation (3-1), in combination with the variables selected by the multiple regression analysis, is used to construct a model. The final equation for predicting the energy consumption during the main wash is:

$$\boldsymbol{CE_{mw} = -0,856 + 0,02 * TEMP_{act} + 0,024 * CW_{mw} + 0,0025 * MWD} \tag{4-4}$$

Where is:

$CE_{mw} = amount\ of\ energy\ consumed\ during\ the\ main\ wash\ in\ kWh$
$TEMP_{act} = actual\ washing\ temperature$
$CW_{mw} = amount\ of\ water\ calculated\ by\ using\ eq.10$
$MWD = main\ wash\ duration\ in\ minutes$

The energy consumed during the spin phase, as well the energy consumed in standby / left on/off mode, is not included in the total energy consumption.

4.2.3 Detergent consumption equation

Analogous to the water and energy consumption prediction equation, the multiple linear regression analysis is used to develop a model for predicting the washing performance index from independent variables: load size, detergent, actual washing temperature and the duration of the main wash.

Basic descriptive statistics and regression coefficients are shown in Table 4-9. The four-predictor model is able to account for 82 % of the variance in the washing performance index.

Table 4-9: Summary statistics, correlations and results from the regression analysis (detergent consumption)

				multiple regression weights	
Variable	mean	std	correlation with WP	b	β
Washing performance (WP)	0,992	0,095			
Load size	4,5	2,39	-0,255***	-0,034584***	-0,868
Detergent	93,9	48,96	0,270***	0,001194***	0,618
Actual washing temperature	42	11,16	0,467***	0,002691***	0,311
Duration of main wash	81	43,71	0,452***	0,001365***	0,652
Constant = 0,812372					
R = 0,907					
R^2 = 0,823					
$R^2_{Adjusted}$ = 0,821					
F= 302,661***					

* p < 0,05 ** p < 0,01 ***p<0,001

Table 4-10: Collinearity statistics

Constant	Tolerance	VIF
Load size	0,552	1,811
Detergent	0,662	1,512
Actual washing temperature	0,942	1,062
Duration of the main wash	0,752	1,330

Tests to see if the data met the assumption of collinearity indicated that multicollinearity is not a concern.

The histogram of standardized residuals indicated that the data contained approximately normally distributed errors, as did the normal P-P plot of standardized residuals, which showed points that were not completely on the line, but close.

The scatterplot of standardized residuals showed that the data met the assumptions of homogeneity of variance and linearity. Based on the results of the multiple regression analysis, the final equation to predict the amount of detergent is constructed.

The general regression equation (3-1), together with the variables selected by the multiple linear regression analysis, is used to construct a model. The result is equation (4-5).

$$\boldsymbol{WP = 0,8124 + 0,0026 * \mathbf{TEMPact} - 0,0346 * \mathbf{LOAD} + 0,0012 * \mathbf{DET} + 0,0014 * \mathbf{MWD}} \tag{4-5}$$

As the equation is intended to be used to calculate the amount of detergent consumed during a washing cycle, it is solved for detergent. The result is equation (4-6).

$$\boldsymbol{DET = \frac{WP - 0{,}8124 - 0{,}0026 * TEMP_{act} + 0{,}0346 * \mathbf{LOAD} - 0{,}0014 * \mathbf{MWD}}{0{,}0012}} \tag{4-6}$$

Where is:

WP = washing performance index
TEMPact = actual washing temperature in °C
LOAD = load of the washing machine in kg
DET = detergent in gram
MWD = duration of the main wash in min

4.3 Results of the virtual washing household modeling approach

The results of programming of the virtual washing household are presented by showing the course of the laundry stock. All examples feature the laundry stock of 15 weeks. In all figures the lines are for visualization purposes only. For the ease of understanding the following examples, the scenario as defined in 3.2.4.2 does not apply and following simplified scenario is assumed.

Each week:	1 kg of 30 °C laundry is added to the stock
	2 kg of 40 °C laundry is added to the stock
	3 kg of 60 °C laundry is added to the stock
Loading factor:	30 °C washing cycle = 50 % of the rated capacity
	40 °C washing cycle = 100 % of the rated capacity
	60 °C washing cycle = 100 % of the rated capacity

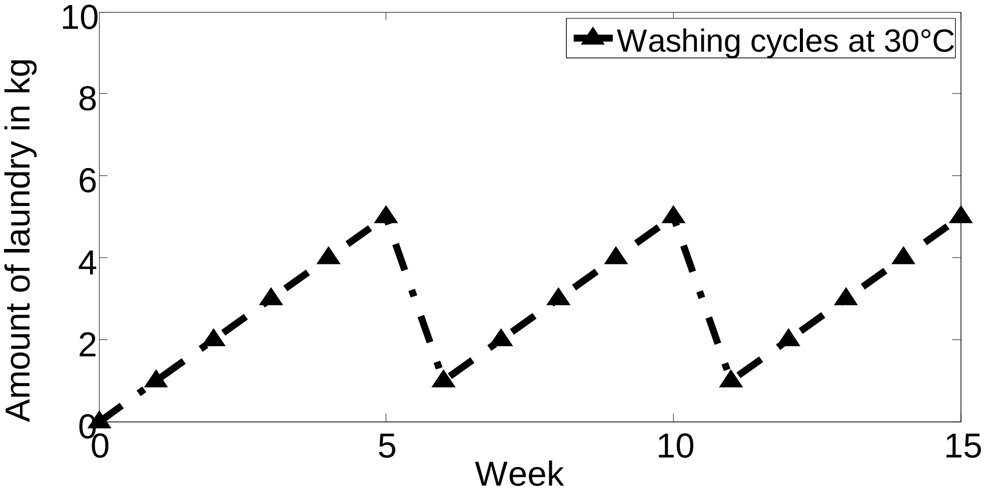

Figure 4-10: Example of 30 °C laundry stock course in a 5 kg rated capacity machine when 1 kg of laundry is added to the stock every week

The results of dynamic simulation of a virtual washing household show the course of the laundry stock of a household that uses a washing machine with the rated capacity of 5 kg. Every week 1 kg of laundry is added to the stock. The washing cycle is conducted when the laundry stock is 5 kg (Figure 4-10).

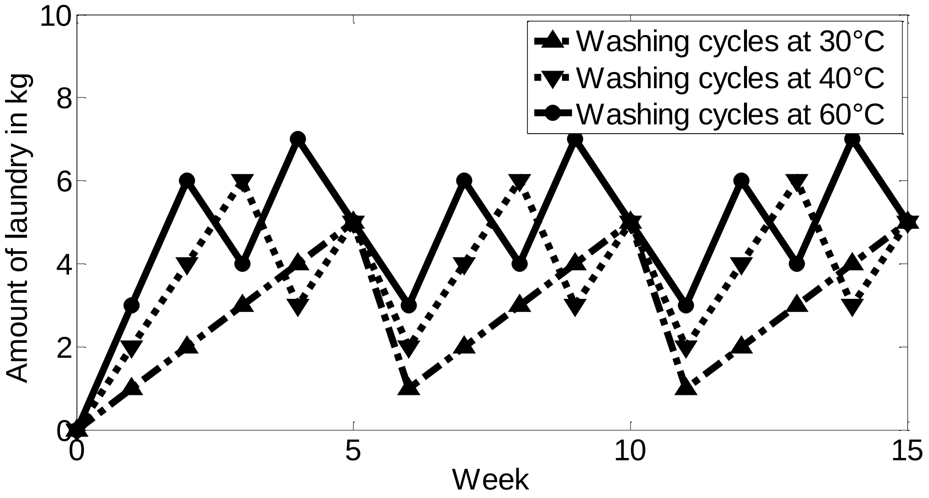

Figure 4-11: Laundry stock course with three different washing programs/temperatures in a 5 kg rated capacity washing machine when every week 1 kg, 2 kg and 3 kg of laundry are added to the 30 °C, 40 °C and 60 °C laundry stock

In addition to the course of 30 °C laundry stock, the courses of 40 °C and 60 °C laundry stock are presented. In the case of the 40 °C laundry stock course, every week 2 kg of laundry is added, and in the case of the 60 °C laundry stock course 3 kg of laundry is added to the stock (Figure 4-11).

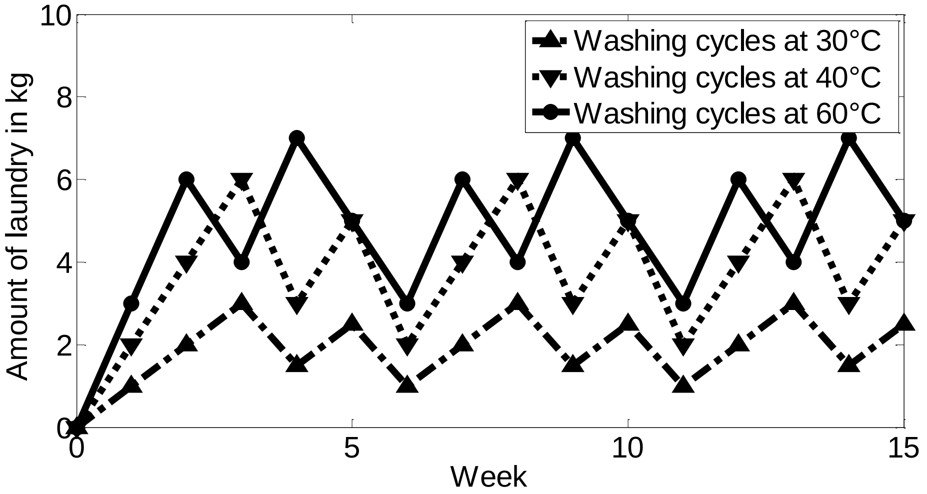

Figure 4-12: Impact of the loading factor (implemented in the case of 30 °C load) on the laundry stock course of three different washing programs/temperatures in a 5 kg rated capacity washing machine when every week 1 kg, 2 kg and 3 kg of laundry are added to the 30 °C, 40 °C and 60 °C laundry stock.

In the case of 30 °C, the load factor of 0.5 is implemented, so that the washing machine conducts a washing cycle when the laundry stock reaches at least 50 % of the washing machine's rated capacity. In the third week, the 30 °C laundry stock reaches 3 kg of which 2,5 kg are washed so that 0,5 kg were left. In fourth week, 1 kg of laundry is added so that the total amount of laundry is 1,5 kg (Figure 4-12).

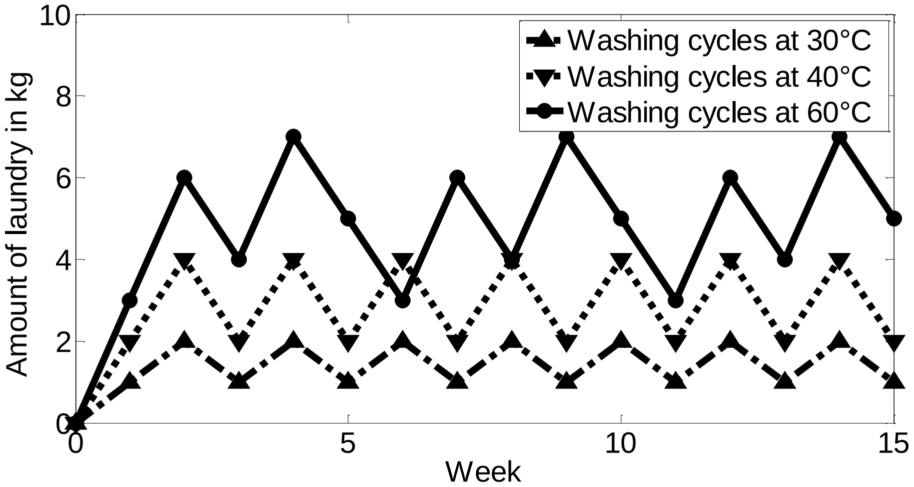

Figure 4-13: Impact of the maximal laundry waiting time (implemented in all three programs/temperatures) on the laundry stock course of three different washing programs/temperatures in a 5 kg rated capacity washing machine when every week 1 kg, 2 kg and 3 kg of laundry are added to the 30 °C, 40 °C and 30 °C laundry stock.The impact is visible in the reduction of the laundry stock in the third week.

Implementation of the maximal laundry waiting time in the simulation routine is visible in the course of all three washing temperatures. The maximal laundry time is set to “up-to-2-weeks”. In the second week, all three laundry stocks are reduced (Figure 4-13).

4.4 Results of yearly simulations

4.4.1 Washing machine’s rated capacity versus household size

The results of the simulation of a yearly usage of the virtual washing machines with the washing machine’s rated capacity (WMRC) of 5 kg, 8 kg, and 11 kg by the virtual washing household are presented. Each data point in the chart shows how much CO_2 equivalent is emitted when the washing machine is used by a household (of different sizes) for one year. The lines are for visualization purposes only.

The following maximal laundry waiting time (MLWT) abbreviations are applied:

MLWT = 0 → maximal laundry waiting time is “up to 1 week”

MLWT = 1 → maximal laundry waiting time is “up to 2 weeks”

MLWT = 2 → maximal laundry waiting time is “up to 3 weeks”

MLWT = 3 → maximal laundry waiting time is “up to 4 weeks”

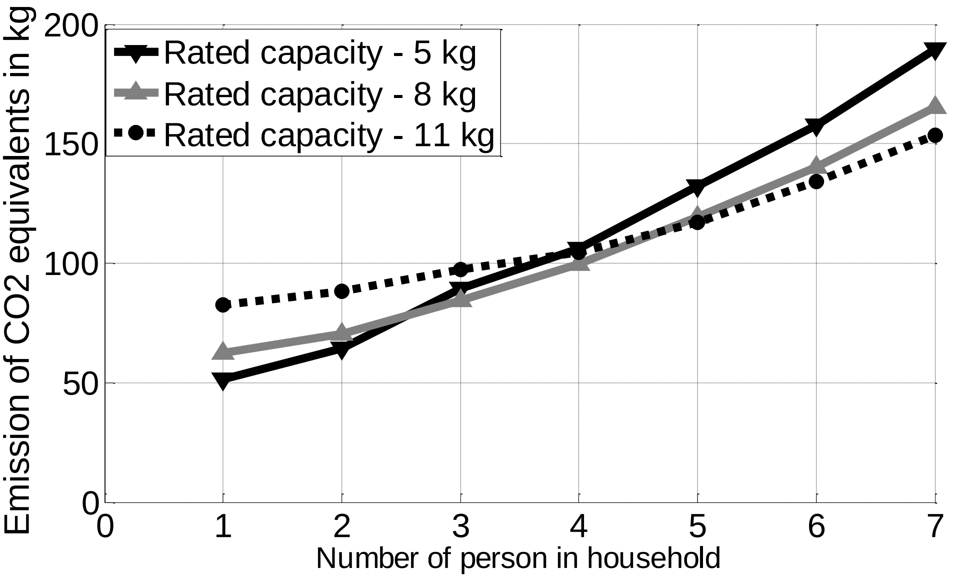

Figure 4-14: Comparison of emission of CO_2 equivalents when MLWT = 0

When the maximal laundry waiting time is “up to 1 week”, the lowest CO_2 equivalents emission values are in the case of 1-person household:

Washing machine with 5 kg WMRC emits 51,4 kg of CO_2 equivalents

Washing machine with 8 kg WMRC emits 62,3 kg of CO_2 equivalents

Washing machine with 11 kg WMRC emits 82,5 kg of CO_2

The highest values are in the case of 7-person household:

Washing machine with 5 kg WMRC emits 187,7 kg of CO_2 equivalents

Washing machine with 8 kg WMRC emits 165,1 kg of CO_2 equivalents

Washing machine with 11 kg WMRC emits 153,5 kg of CO_2 equivalents

Slopes of washing machines with 8 kg and 11 kg rated capacity interchange in the case of a 4-person household. The slopes of washing machines with 5 kg and 8 kg rated capacity interchange between the household sizes of 2- and 3-persons.

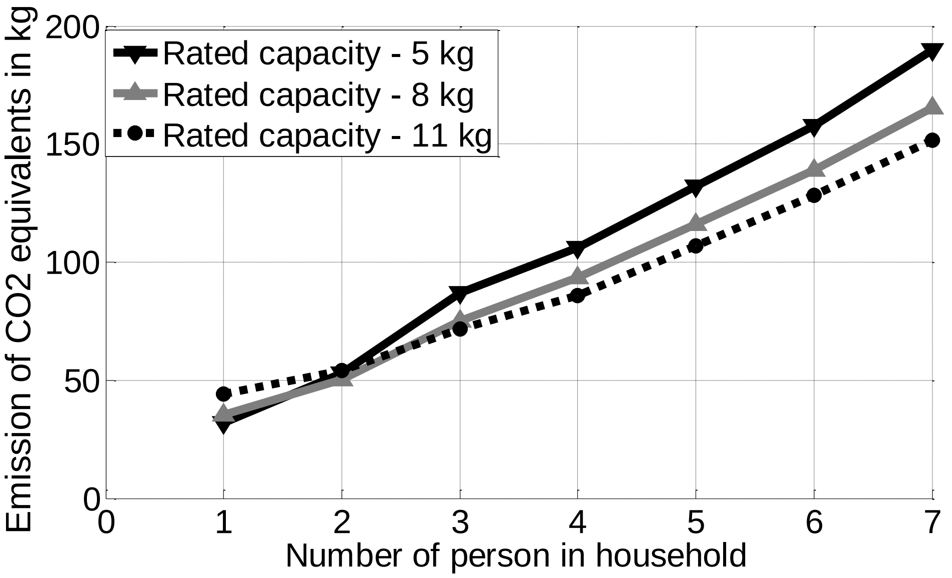

Figure 4-15: Comparison of emission of CO2 equivalents when MLWT =1

When the maximal laundry waiting time is “up to 2 weeks”, the lowest values are in the case of 1-person household:

Washing machine with 5 kg WMRC emits 51,4 kg of CO_2 equivalents

Washing machine with 8 kg WMRC emits 62,3 kg of CO_2 equivalents

Washing machine with 11 kg WMRC emits 82,5 kg of CO_2 equivalents

The highest values are in the case of 7-person household

Washing machine with 5 kg WMRC emits 187,7 kg of CO_2 equivalents

Washing machine with 8 kg WMRC emits 165,1 kg of CO_2 equivalents

Washing machine with 11 kg WMRC emits 153,5 kg of CO_2 equivalents

Slopes interchange at 2-person household tick mark.

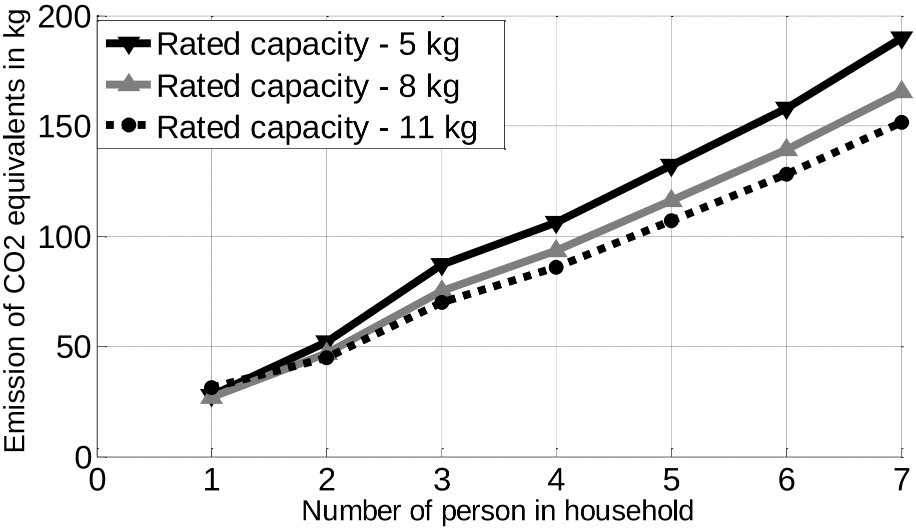

Figure 4-16: Comparison of emission of CO_2 equivalents when MLWT =2

When the maximal laundry waiting time is “up to 3 weeks”, the slope of the washing machine with a rated capacity of 8 kg and 5 kg have the lowest CO_2 equivalents emission values for a 1-person household with 27 kg (WMRC = 8 kg) and 27,6 kg (WMRC = 5 kg). The highest CO_2 equivalents emission is in the case of the washing machine with a 5 kg rated capacity (189,7 kg). The interchange of the slope course is at the 1-person household tick mark.

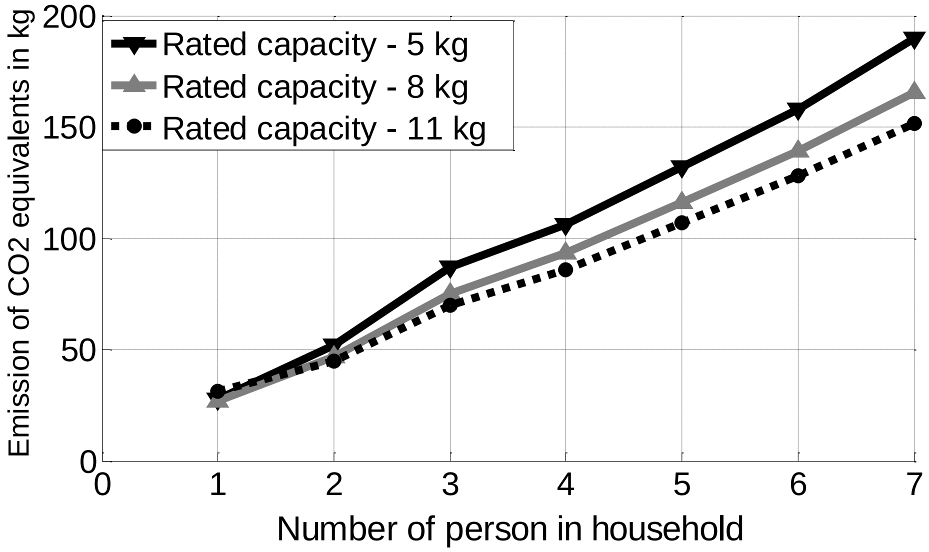

Figure 4-17: Comparison of emission of CO_2 equivalents when MLWT = 3

When the maximal laundry waiting time is “up to 4 weeks”, the lowest values of CO_2 emission are in the case of the washing machine with a rated capacity of 8 kg and a 1-person household with 24,8 kg of CO_2 equivalents emitted. The highest values of CO_2 equivalents emission are in the case of the washing machine with a rated load capacity of 5 kg with 189,7 kg in the case of a 7-person household.

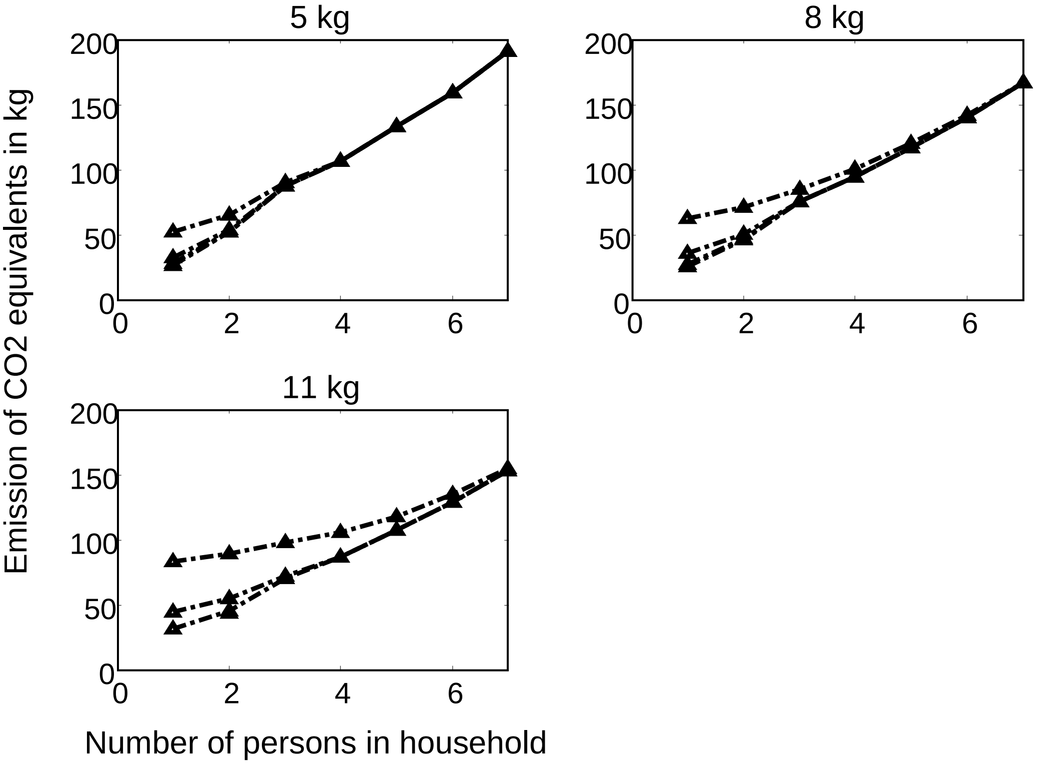

Figure 4-18: Overview of washing machine's rated capacity vs. MLWT

An overview of all washing machines in dependence of the maximal laundry waiting time show a strong gap between the slopes of the curves as the loading capacity of the washing machine increases.

4.4.2 CO_2 equivalent emission of water detergent and energy

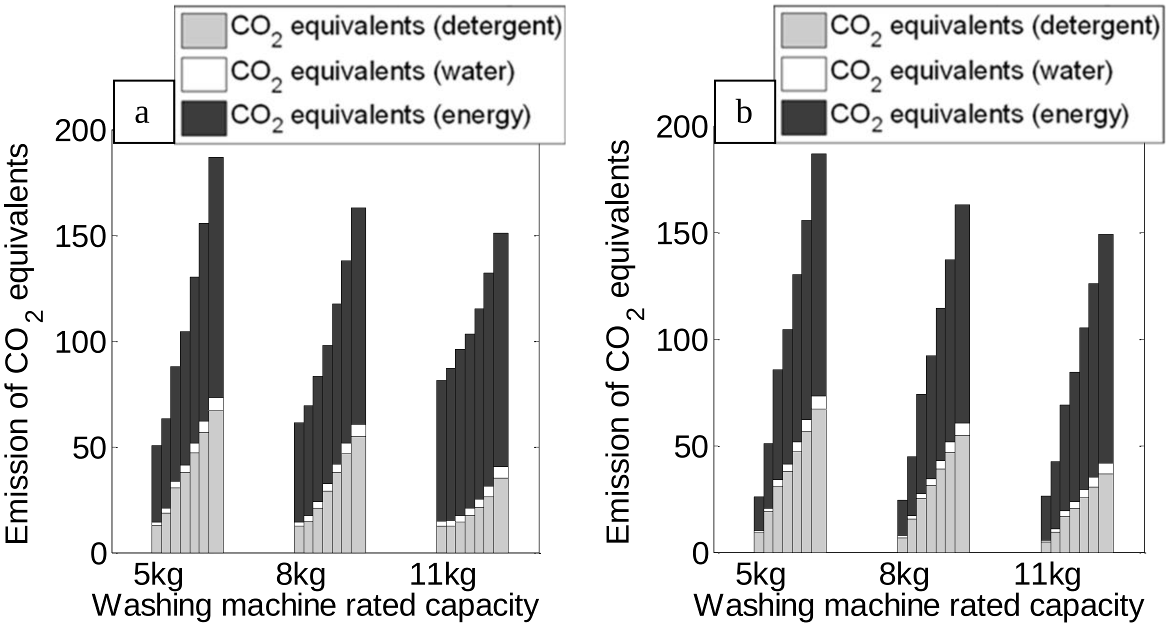

Figure 4-19: CO_2 equivalents emission split by individual resource consumption share where MLWT = 0 (4-19a) and MLWT = 3 (4-19b). Each of the seven columns within each rating capacity class represents household ranging from 1-person households (First column) to 7-person households (Seventh column).

CO_2 equivalents emission is split by the individual share of the resources consumed. The share of the energy and detergent in the total CO_2 equivalent emission are the highest. The share of the CO_2 emission for water is minimal.

4.4.3 Comparison of the time exposure[4]

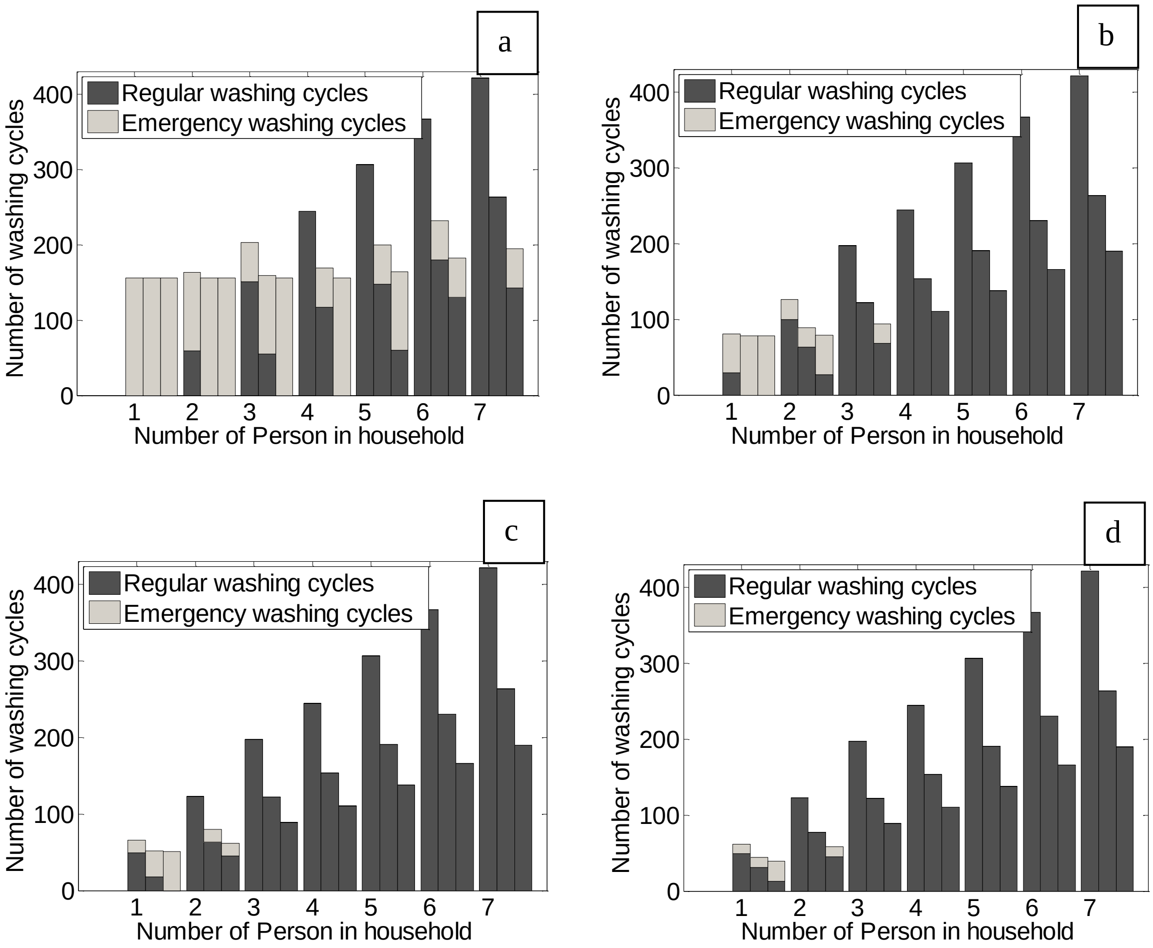

Figure 4-20: Time exposure in dependence of the rated capacity, household size and MLWT (Starting with maximal laundry waiting time of “up to 1 week” (Chart a) to maximal laundry waiting time of “up to 4 weeks” (Chart d)).

Time exposure depends on the maximal laundry waiting time, washing machine’s rated capacity and the number of persons in the household. Figures a-d show the time exposure in dependence of the maximal laundry waiting time. The time exposure is the highest when the maximal laundry waiting time is the lowest. With an increase of the

---

[4] Time consumed for washing (expressed in number of washing cycles). It is composed of the regular washing cycles (cycles where the rated capacity of the washing machine is used) and emergency washing cycles (cycles where the washing machine’s rated capacity is not used due to reaching the maximal laundry waiting time).

maximal laundry waiting time, the total time exposure as well as the share of the emergency washing cycles decreases.

4.4.4 Comparison of average washing temperatures[5]

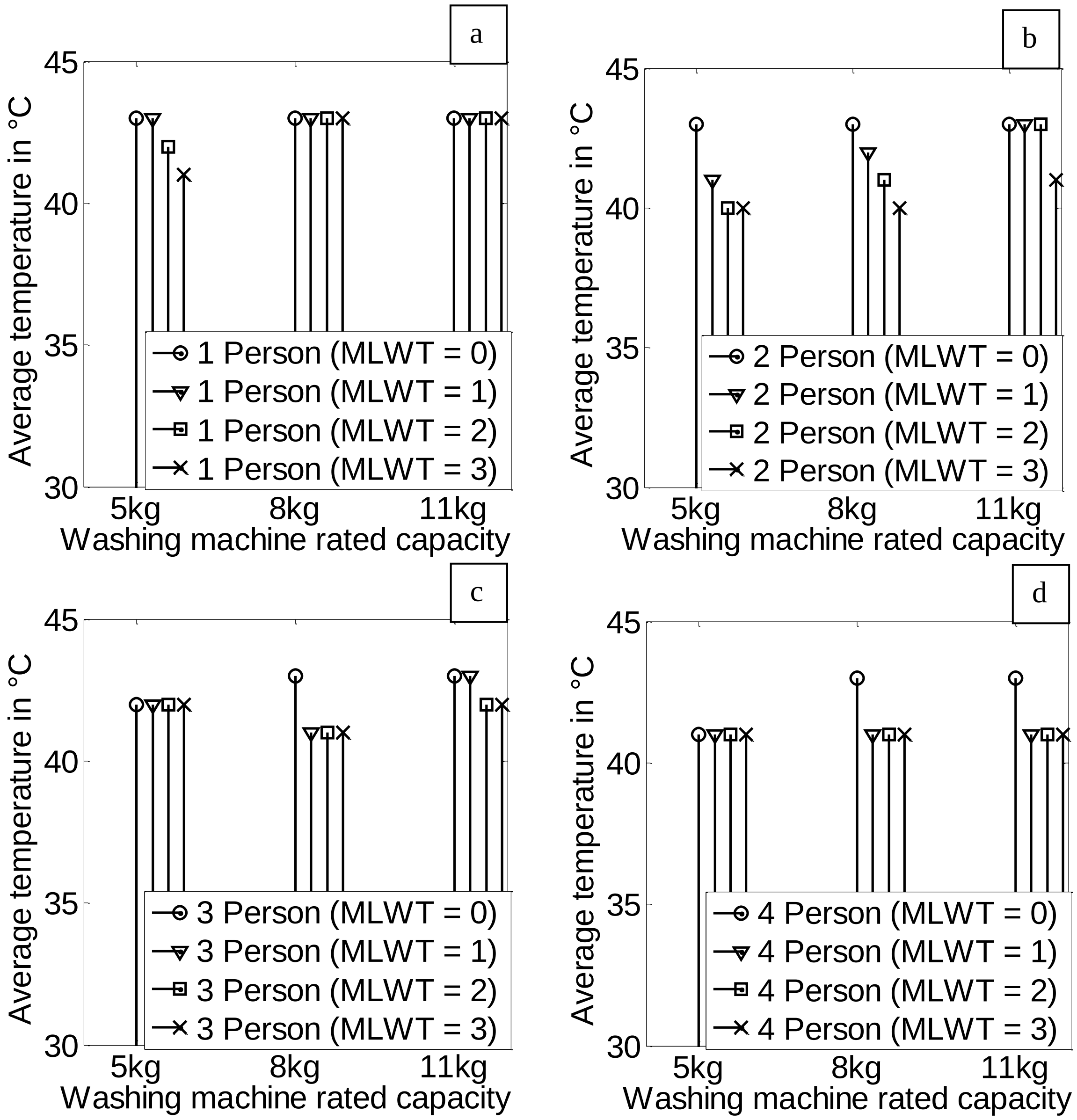

Figure 4-21: Comparison of average washing temperatures in dependence of the household size: 1-person household (4-21a) – 4-person household (4-21d)

---

[5] Arithmetically-averaged washing temperature of all washing cycles conducted during one year

With an increase of the maximal laundry waiting time, the average washing temperature decreases. The values are the lowest when the maximal laundry waiting time is “up to 4 weeks” (40 °C e.g. 2-person household). The highest values are in the case when the maximal laundry waiting time is “up to 1 week” (43 °C in e.g. 1-person household).

5 Discussion

5.1 Virtual washing machine

The first goal of this study was to develop a model of a virtual washing machine that is based on the data of washing machines available on the market. Although three equations are necessary to describe the washing process, it can be concluded that the goal of a construction of a virtual washing machine is reached.

The fact that three equations are necessary to describe the washing machine process is due to its complexity. On one hand, there are numerous variables that impact the process, and on the other hand there are three dependent variables where each has to be calculated by using a separate predicting model. In the following, the individual equations are discussed.

5.1.1 Equation for calculation of water consumption

The function of water in the washing process is manifold. It is not only the medium that transports the detergent and heat to the fabric surface and facilitates the removal of the soil, but it is also the medium where the soil is stabilized so that a redeposition is prevented. (JAKOBI *and* LÖHR, 1987)

Since 1970, numerous inventions have led to a decrease of the water consumption. Average water consumption of 200 liters in 1970 (STAMMINGER *et al.*, 2005) decreased to today's consumption of 42,6 liters (VHK, 2013).

The data of the washing machine's tests (Figure 4-1 and Figure 4-2) and the resulting equation show that load size and rated capacity are the two most influential factors on the water consumption of a washing machine.

However, data also reveals that there are many variations among washing machines in their ability to adapt the water consumption to the load, especially when they are not fully loaded. In some cases, the specific water consumption for washing nearly same amount of load can vary up to double the amount when the washing machine is underloaded (Figure 4-2).

As the washing machines test data shows, the differences among washing machines' abilities to adapt the water consumption to the load is lowest when the washing machine is fully loaded. This is confirmed also by (RÜDENAUER *et al.*, 2004), who also found out that with a decrease of the load size, the specific consumption of the water and energy increases.

The consumers, however, do not fully load their washing machine. They consider, for example, a load of 3,7 kg to be a full load in a washing machine which has a rated capacity of 5 kg (KRUSCHWITZ *et al.*, 2014). In order to lower the resource consumption, most of today's washing machines are equipped with sensors that control the washing machine and automatically adapt the resource consumption to the load. With a decrease of the load size, the water consumption decreases. (WAGNER, 2011)

As data shows, this is not always the case.

The fact that fully loaded washing machines show the lowest variance in the water consumption might be viewed as a direct consequence of the energy label standard EN60456:2005, which was in force when the tested washing machines were produced. The standard stipulated that washing machines are to be tested with a full load when tested according to the energy label. There was no incentive for the manufacturers of white goods to optimize the washing machines to anything other than full-load size.

The reason for variations in the water consumption when the washing machine is not fully loaded, however, might be because of the accuracy of the sensor and fuzzy logic implemented. It is possible that the sensors do not react precisely, and therefore influence the fuzzy inference so that variations in water consumption occur.

The data shows that the washing machine's rated capacity influences the water consumption as well. Washing machines with a higher rated capacity have higher absolute water consumption; however, with an increase of the load size, the specific water consumption decreases. A possible reason for this is that washing machines let in some amount of water, whether it is loaded or not. This minimal amount of water is needed for the protection of the washing machine namely some of its components, such as the heater, which might suffer damage when preheating and running without water that would absorb the heat. In washing machines with a higher rated capacity, this minimal amount has a lower impact on the specific water consumption than in the case of washing machines with a lower rated capacity.

5.1.2 Total water consumption

Total water consumption depends mainly on the number of rinsing cycles (WAGNER, 2011). The number of the rinsing cycles again depends on what the manufacturer wants to offer to its consumers as a standard program.

In some cases, the consumers are offered a washing program with a lower number of rinsing cycles as a standard, and the consumers have to use additional options such as "*water plus*" or "*extra rinsing*" in order to receive a higher rinsing performance.

Alternatively, some manufacturers offer the consumers a washing program with a higher water consumption, i.e. with more rinsing cycles as a standard washing program and it is up to the consumers to include the water-saving options, such as *"economy wash"* or *"half load"* in order to save water.

In some cases, even the sensors that monitor the washing process can influence the water consumption. For example, the number of rinsing cycles can vary depending on the quality of the foam detection sensors.

A look into the comparison of the average values of *total water consumption* to *main wash water consumption* reveals that this ratio is 1:3,5 no matter whether the detergent dosage is nominal, under- or overdosed. Assumption that the fuzzy logic would adapt to the water consumption if the amount of detergent is overdosed is not met.

A possible explanation for this might be because of the detergent used for washing tests. In this case, the EN60456:2005 standard detergent A* is used, where the amount of foam inhibitor is very high. For this reason it is possible that the foaming detection sensors recognize that no further rinsing cycles are induced.

Another reason for this might be because of the washing program design of the tested washing machines. It might be possible that the number of the rinsing cycles is not sensor/fuzzy logic controlled and a standard number of rinsing cycles is included in the washing process.

Energy consumption

In a washing machine, energy is consumed for heating the water, running the main motor and the drain pump, as well as for running the sensors, control processor and other electronic signaling units of the washing machine. During the washing machine's test, the energy consumption of the processor and signaling unit were not measured.

About 91,9 % in the variation in energy consumption can be explained by independent variables: actual washing temperature, water consumption, and the duration of the main wash. This coefficient of determination value can be considered to be good when the afore-mentioned variances among different washing machines are taken into account.

The most energy, however, is consumed for electrically heating up the water, especially when the inlet water is not preheated (KUTSCH *et al.*, 1997; SMULDERS, 2007; WAGNER, 2011). This is also confirmed by the data received in the washing machine's test. With an increase of the temperature, the energy consumption increases. The higher the washing temperature, the more energy is needed to heat up the water, hence more energy is consumed. (SMULDERS *et al.*, 2007)

The data, however, shows differences in energy consumption among different washing machines and different load sizes. Since the water consumption strongly depends on load size, the energy consumption indirectly also depends on the load size, so that the dependencies discussed in 5.1.1 also apply here.

Furthermore, the data shows that some washing machines do not always heat up the water to the preset temperature (Table 4-5). For example, WM9 reaches, in a nominal 60 °C program, a maximal actual washing temperature of 47 °C.

The reason for this might be in the specification given in the Eco-design regulation. According to it, the washing machines have to reach a certain washing performance index. In a reference 60 °C program, a washing index of 1,03 is required. In practice this means that the manufacturers have to provide one program for each washing machine that fulfills those conditions, and this program is to be used when the washing machine is tested. It is up to the manufacturer to find a perfect combination of the washing factors so that the required washing performance can be achieved. In order to save energy, some washing machine producers lower the actual washing temperature and increase the main washing time. VAN HOLSTEIJN EN KEMNA, 2013 also observed this trend of prolonging the washing cycle in washing machines, which "*opens the possibility to wash with lower temperatures with the same washing result and can therefore increase the energy efficiency.*" (VHK, 2013, p.41) They see a risk in those longer cycle times, in such that "people might not use the energy efficient program but will use the normal cotton program instead. They might simply not have the time to wait for 5 hours before they can start the next load." (VHK, 2013, p.41)

Due to this discrepancy between the nominal washing temperature and the actual washing temperature, in the energy equations the maximally reached actual washing temperature is included. With beta values of 0,72 (Table 3-1), the washing temperature's contribution to the explanation of the variance is the highest. The contribution of the duration of the main wash is roughly as high as the contribution of the water consumption to the explanation of the variance.

Analogous to the water consumption, the real energy consumption also depends on what the manufacturer wants to offer to the consumer as a standard washing program. In some cases, the manufacturer offers a shorter program as standard and the consumer has to use the "*intense*" or "*stains*" option to extend the program. Other manufacturers offer a longer washing program as a standard program, and the consumer has to choose the "*express*" or "*short*" option in order to shorten the washing program.

However, under certain circumstances, even the duration of the main wash has more influence on the energy consumption than the chosen temperature. In those cases when a low washing temperature and long duration of the main wash is selected (which are, for example, the case in an eco-program), the share of the energy consumed for heating up the water is lower than the share of energy consumed by the engine.

In the equation eq. (4-4), the constant (y-intercept) is -0,836 kWh. Assuming that all the explanatory variables are set to 0, the value of the response variable would be negative. However, as seen in the equation for the calculation of water consumption, 4,01 L of water is always consumed, and its temperature is higher than 0 °C in order to be even in fluid state and hence added to the washing machine. For this reason the validity of the equation is limited.

5.1.3 Detergent consumption

The equation for calculating the detergent consumption is based on a multiple regression that sets the washing performance in relation with the load size, duration of the main wash, actual washing temperature and amount of detergent. The final equation is then developed by solving the equation for detergent.

Consumer behavior influences the outcome of a washing cycle. In a washing cycle, the consumer has to decide (1) how much of laundry to load, (2) what washing program (temperature, duration, spinning speed, rinsing characteristics) to choose, and (3) what kind of detergent to use and how much to dose. In the equation, some of those consumer patterns are included, and each can be adjusted separately.

The washing machine test data shows that the load size has a strong impact on the washing performance (Figure 4-6). The beta values of the multiple regression analysis (Table 4-9) show that the load size actually has the highest impact on the washing performance index of all variables. A negative B value of the load (-0,034584) indicates that every *ceteris paribus* increase of the load size results in a decrease of the washing performance index.

In accordance with SINNER 1961, with a lower load size the free space in the drum increases and hence the laundry has more space to tumble down, increasing the mechanical force. When all other factors are kept constant, an increase of the washing performance index occurs.

The virtual washing machine offers a set of input parameters (e.g. load amount, washing temperature, etc.), in which each can be individually varied. Only those variables that can actually be chosen by the consumer are included in the model. A washing program can be simulated by combining/varying those parameters.

- Temperature: Washing temperatures between 30 °C and 60 °C can be preset in the equation. As previously discussed in chapter 5.1.2, there is a discrepancy between the nominal and actual washing temperature.

- Duration of the main wash: In real-life washing machines, there is not a possibility to preset the duration of the main wash in the same manner as is possible with the washing temperature or the spin. However, with time consumers learn which washing programs are short and which are long, and choose the respective program when needed. By doing so, consumers are able to influence the duration of the washing program. Another possibility to influence the duration of the main wash is by choosing other options, such as the “short” or “intense” option.

There are also some limitations of this “virtual program” in comparison to the real-life washing programs. For example, some washing programs interrupt the main wash program with spinning cycles in order to facilitate the wetting process. However, in this virtual washing machine those specific program designs are not implemented.

The data shows that with a decrease of the average washing temperature, the washing performance index decreases. This fact also shows that there is a potential for tradeoff between the washing temperature and the washing performance. Furthermore, there is also interdependency between the washing performance and the amount of detergent (Figure 4-8). This bears a potential for a tradeoff for consumers who have to wash textiles for which a lower washing performance is acceptable (e.g. slightly soiled textiles). In those cases, where there is no need to have a high washing performance, consumers can lower the washing temperature and thus save energy. Alternatively for the consumer, there is a possibility to lower the amount of detergent.

5.2 Virtual washing household

The second goal of the present work is to develop a model of a household washing behavior that incorporates the household- and behavioral parameters.

The mathematical model presented in 3.2.3 differs from models presented by other research because it does not calculate with a fixed load size, but rather varies during the simulation in accordance with model settings. Furthermore, it allows a variation of certain parameters such as: number of persons in household, amount of load per person, and shares of different program/temperature batches of the total amount of load.

An important variable in the model of the virtual washing household is the loading factor (Figure 4-12).

Most of the mathematical models presented by other researchers are very simple, and in most cases the calculations are done by assuming the consumer uses a full load (or possibly a half load). A loading factor, which depends on the type of laundry, is not included in such calculations.

The consumers, however, do not use the full capacity of the washing machine. According to STAMMINGER, 2011, 10 % of consumers in Europe load the washing machine in dependence of the type of laundry, and 63 % load the washing machine without overloading it. Consumer associations also promote fully loading the washing machine, except when washing delicates, in which case a half load is recommended (ForumWaschen, 2013). By using the virtual washing household model, it is possible to include all different loading factors that differ in dependence of the type of laundry that has to be washed.

The key moderating parameter in this simulation design is the maximal laundry waiting time parameter (Figure 4-13).

With this variable, it is possible to add a time dimension to the virtual washing household model and so explore the effects that might occur when the consumer is ready to postpone an action (in this case the washing of laundry) to a later point of time. For example, “being in hurry” can be simulated by shortening the MLWT and “environmentally conscious” behavior can be simulated by extending the maximal laundry waiting time.

In this work, it is possible to simulate the usage of a washing machine, in a parallel manner, by households of different sizes. Comparison of the usage of the same washing machine by households (of up to seven persons) helps to reveal how the household size influences the consumption.

5.3 Simulations

The third goal of the present work is to develop and conduct simulation of the usage of the virtual washing machine by the virtual washing households. By conducting parallel simulations and by varying device-, household- and behavioral parameters, a parameter combination with the lowest environmental impact can be determined, and hence conclusions regarding an optimal consumer behavior can be drawn. In order to answer this question, the following aspects are examined:

- Washing machine’s rated capacity
- Resource consumption
- Washing frequency
- Average washing temperature

5.3.1 Washing machine's rated capacity

Environmental impact of automatic washing depends not only on the household size and the washing behavior (i.e. maximal laundry waiting time), but also the washing machine's rated capacity.

Comparison of the slopes in Figure 4-14 shows that when the maximal laundry waiting time is very low, households with a lower number of persons would have the lowest impact on the environment when using a washing machine with a lower rated capacity. A washing machine of 8 kg or even 11 kg would be less adequate in such a case.

With an increase of the number of persons in the household, a washing machine with a higher rated capacity becomes more adequate. With an increase of the maximal laundry waiting time, the amount of laundry that accumulates in a household increases further. In such a case, a washing machine with a higher rated capacity becomes more adequate due to use of the economies of scale potential of such washing machines (Figure 4-15 - Figure 4-17).

A usage of washing machines with a higher rated capacity by smaller households (for example 1-3 person households) demands change of the behavioral patterns. One possibility is that the household increases the maximal laundry waiting time and waits until enough laundry is accumulated so that the rated capacity of the washing machine can be used. However, it is questionable whether the consumers are willing to wait for three or more weeks until enough laundry is accumulated.

Another possibility for more sustainable usage might be in combining the different washing loads. For example, by combining a 30 °C and 40 °C washing load, and by choosing the washing temperature in accordance with the recommendation of the most sensitive laundry piece, and in combination with prolonging the washing cycle, the same washing performance at a lower resource consumption may be achieved.

(JUNGBLUTH *et al.*, 2006) as well as (JANCZAK *et al.*, 2010) have already shown that lowering the temperature to the next possible level and prolonging the washing time leads to a decrease in the energy consumption while the washing performance remains the same.

It should also be kept in mind that a continuous usage of lower temperatures may generate some other issues, such as problems with hygiene. In such cases, the usage of appropriate washing detergent, such as a bleach-containing detergent, could help to resolve those issues. Furthermore, in this respect, the consumer should consider following the suggestions of the consumer association to cyclically wash at higher temperatures, and to leave the door and the detergent container open after a washing cycle.

5.3.2 Resource consumption

The resource consumption comparison shows that energy and detergent have the highest share in CO_2 emission. The share of the water is not very high. The reason for this is that the water consumption has been optimized in the past decades. According to the EuP preparatory study, water consumption has reduced from 1997 to 2005, with an annual improvement of 0,28 l / kg (PRESUTTO *et al.*, 2007).

The contribution of the energy to the total CO_2 emission is highest when a smaller household uses a washing machine with a higher rated capacity and the maximal laundry waiting time is very short. In such a case, the household never uses the rated capacity of the washing machine as shown in the model. With a lower amount of load, the mechanical work is increased (SINNER, 1961) and therefore a lower detergent dosage is needed to reach the preset washing performance. In such cases, the energy related CO_2 equivalent emission is more than three times higher than the CO_2 equivalent emission of detergent (Figure 4-19).

For the calculations of the energy consumption, it was assumed that an energy mix is used, where a certain portion is produced using nuclear-, coal- and renewable energy sources. In this case, the CO_2 equivalent conversion factor for energy is 600 g / kWh. In an energy mix with a lower CO_2 equivalent emission (which might come in the future), the detergent consumption might have a higher influence on the CO_2 emission than the energy consumption.

On the other hand, it is also possible that more advanced technology in detergent production might occur, which then could lead towards a lower impact of the detergent on the CO_2 equivalent emission.

In both cases, there is a potential for tradeoff between the energy and the detergent that could be used in order to have an even more sustainable behavior.

5.3.3 Washing frequency

The time consumed for washing purposes is also an important factor when evaluating the different washing behavior patterns. Although the time consumed for washing purposes includes the washing machine loading/unloading time as well as the washing time, in this research the washing frequency solely represents time consumption.

One of the arguments for selling washing machines with a large load capacity is that it is time saving, since more loads can be washed at the same time, hence the consumers are able to reduce the number of washing cycles when using those washing machines. However, this depends on the household size and the washing machine's rated capacity, as well as on the consumer behavior when using the washing machine.

As presented in the data (Figure 4-20), two different washing cycles are to be distinguished. The first one is a "normal washing cycle", in which the washing machine's rated capacity (adjusted for the load factor) is fully utilized. The second one is an "emergency washing cycle", in which the washing cycle is conducted no matter how much laundry is loaded.

The behavioral factor that influences the frequency of emergency washing cycles is the maximal laundry waiting time. For example, when the maximal laundry waiting time is "up to 7 days" there is almost no difference if consumers use 5 kg, 8 kg or even 11 kg washing machine in cases of one-person and two-person households. In all those cases, the washing machine's rated capacity is not fully used, which means that most of the washing cycles are "emergency washing cycles" and hence no time is saved.

With an increase of the household size, the number of emergency washing cycles decreases, and the differences among washing machines regarding the washing frequency becomes more visible.

An exception is the 11 kg washing machine, in which the emergency washing cycles also occur in the case of a 7-person household, when the maximal laundry waiting time is low. The reason for this is that even a 7-person household does not have enough 60 °C laundry which can be collected in such a short time in order to use the rated capacity of the washing machine. However, with an increase of the maximal laundry waiting time, the number of emergency washing cycles decreases here as well.

The consequences of the washing frequency are manifold:

- Firstly, high usage frequency might be stressful for the consumer. For example, those consumers whose work life allows washing only on weekends, or consumers who use a community washing machine, might experience the high washing frequency as very tedious. It is possible that in such cases those consumers, in order to be able to wash more washing cycles in a shorter period of time, chose to use a shorter washing program that might be inadequate from the resource consumption, hygienic or/and general cleanliness perspective.
- Secondly, with an increased frequency, a fatigue of material in the washing machine, such as the drum casing bumpers, could undergo damage, as well as a lower life expectancy of the washing machine. ÖKO-INSTITUT calculates that a washing machine can be used for 1840 washing cycles (RÜDENAUER *et al.*, 2004). A non-optimal usage might shorten the life expectancy of a washing machine.

5.3.4 Average washing temperature

Data received from the washing machine test and the eq. (4 4) show that the energy is directly correlated with the chosen washing temperature. In order to lower energy consumption, washing at lower temperatures is promoted. Since the early 1970s, the average washing temperatures have declined. This is a good indicator for the promotion of a more environmentally friendly behavior (AISE, 2013).

As the data shows (Figure 4-21), the influence of the maximal laundry waiting time on the average washing temperature is also highly important. With an increase of the laundry waiting time, the rated capacity of the washing machine is used more often (which is especially the case of the 60 °C washing cycles, in which the loading factor is highest), and hence the average washing temperature decreases. This finding is of high importance for two reasons:

Firstly, consumer associations' promotion of lower temperatures has often encountered a resistance among consumers, due to probable perceived washing performance inefficiency. A possible solution to this problem might be in promoting the extension of the maximal laundry waiting time, which then would induce the use of the washing machine's rated capacity, and therefore might lead to a decrease of the average washing temperature.

Secondly, those consumers who do not wish to decrease the washing temperature due to fear of hygiene-related issues can, at least to some extent, contribute to environmental protection by increasing the maximal laundry waiting time and so lower the household average washing temperature.

Furthermore, the data shows that the effects of decreasing the average washing temperature while increasing the maximal laundry waiting time occur in dependence of the washing machine size and the household size.

For example, a washing machine with a 5 kg rated capacity used by a 1-person household has a potential to lower the average washing temperature when increasing the maximal laundry waiting time. However, usage of an 11 kg washing machine by a 1-person household does not bear such a potential.

It can be concluded that there is an optimal washing machine's rated capacity for each household size.

5.4 Deficits of the presented research

Although the virtual washing machine and the virtual washing household display a robust predicting power, there are still some aspects which should be critically observed.

In the present work, the hygiene and the soil re-deposition were not a subject of research. However, those aspects should also be considered, because the hygiene aspect in laundry washing, as well as the soil re-deposition, is increasing, which is something the consumers are able to evaluate at the end of a washing cycle. This could induce a behavioral change towards rewashing the laundry, or usage of less resource-saving programs, such as intense or water plus programs.

The duration of the main wash in the virtual washing machine model is automatically selected in dependence of the washing machines' rated capacity. The values used are average values of the individual washing machines groups. Such an approach is certainly valid in order to predict the resource consumption of tested washing machines. However, generalizing all washing machines should be used with caution.

In the virtual washing machine, the rinsing cycles are not part of the model and a constant factor is included instead. Such a simplified approach allows for an estimation of the resource consumption, but the model does not allow the inclusion of consumer behavior in usage of rinsing options (water plus option or sensitive option). An inclusion of the rinsing cycles in the model would enhance the model and make it more precise in predicting the water consumption.

The virtual washing machine model allows for the prediction of energy consumed during the main wash. However, although the share of energy consumed during the rinsing phase and spinning phase, as well as in the standby mode, is not as high as the energy consumed during the main wash, its inclusion in the virtual washing machine model would allow a more precise prediction of the resource consumption.

Detergent used for the washing machine test is A* detergent as specified by EN60456:2005. Usage of A* detergent helps to compare the washing machines. Commercially available detergents used by consumers, however, differ significantly.

Commercial detergents contain advanced components (e.g. enzymes) that allow lower dose amounts without lowering the washing performance. Inclusion of the commercial detergent in the model would provide an even more precise picture of the influence of washing on the environment.

In the case of the virtual washing household, it was assumed that the household displays an ideal behavior when washing laundry. However, this is not the case in real life. Such an approach only helps to illustrate the real-life behavior to some extent. There are many parameters that influence the consumer behavior such as the gender age of the participants or even seasonal aspects which are not included in this research. An inclusion of those aspects would help to explore the consumer behavior more thoroughly.

6 Conclusion

Based on the data of different washing machines, a model of a virtual washing machine was developed and, despite the large differences among the tested washing machines, it shows a robust predicting power.

The developed virtual washing household model offers a high range of possibility to simulate some of the consumers’ behavioral patterns. Its dynamic development of the laundry stock course and possibility to vary household and washing machine parameters makes this model more advanced in comparison to the modeling solutions described in the literature.

The virtual washing household model, used in this work, could also be used to simulate usage of other household appliances. For example, the virtual washing household model could also be used to simulate the usage of automatic dishwashers or tumble dryers. By extending the model to more household appliances, a more precise resource consumption-predicting model could be established and used to predict the daily energy consumption and possible peak demands. Furthermore, it would enable a simulation of more precise trend developments so the policy making decision could be supported.

In connection with this, the variable maximal laundry waiting time has proven to be of great help in adding a “sustainability component” to the consumer model. At present, no research has evidenced the usage of such a moderating factor that has been presented in the literature. The maximal laundry waiting time parameter is of great value due to its ease of use and its ability to support the increasing value of information that must retrieved in behavior-related simulations. Furthermore, it reflects real-life behavior very well, in cases where consumers do not wash the same amount of laundry every week, but instead only wash when there is enough laundry or when certain loads have to be washed, regardless of whether the rated capacity is fully used or not (emergency washing cycle). For this reason, it should be included as an eventual standard variable in future models where the sustainability-related consumer behavior is being explored.

7 Future prospects

In the present study, the amount of laundry added to the washing machine, as well as the rated capacity of the washing machine are each expressed in kilograms. However, in some cases the declared increase of the washing machine’s rating capacity is not followed by a volume increase of the washing machine’s drum. In such cases, the resulting overload of the drum and consequent decrease of mechanical work (Sinner, 1960) is substituted by an increase of the other washing factors, such as the washing time.

For this reason, in a follow-up model of the virtual washing machine, it would be important to include the washing machines’ drum volume instead of the rated capacity expressed in kilograms.

Furthermore, in the following study the actual washing temperature is measured in the sump (that is, in the space in-between the inner and outer drum at the bottom of the washing machine’s drum). This temperature is not necessarily the same as the temperature in the load (especially at the spot where textile, soil and wash liquor meet). However, the temperature at this spot is actually influencing the washing performance. An inclusion of this parameter in a future follow-up virtual washing machine model should be considered so that it might lead to a more accurate model.

In addition, for the washing machines’ tests, cotton was used as a test load. In an eventual follow-up model, other fabrics such as synthetics should also be included as test loads. This would allow for a more realistic, real-life relevant model. Additionally, in the follow-up model other detergents (liquor detergent, commercial detergent, etc.) and new washing machines models (e.g. models that use heat-pump and/or automatic dosing) should be included.

The virtual washing household model also bears potential for improvement. In the presented study it was assumed that the consumer washes every temperature-specific load separately. In real life, however, this is not the case and the consumers often combine two (temperature/program) batches of laundry together. A possible optimization of the model should also include such behavioral patterns in the simulation.

Furthermore, additional research is necessary to identify the driving forces of non-optimal consumer behavior (e.g. lack of time, habit to wash every week, convenience of always having clean laundry or to wash on specific weekdays). The findings of such research could, together with findings of this study, be used to develop practicable tools that stimulate more sustainable behavior. Such tools could be used to promote the increase of the maximal laundry waiting time. For example:

- Consumer associations could develop an info brochure informing consumers to separate the laundry not only by the color/soil level or type of textile, but to also include a “washing priority” category.
- Consumer associations could develop advising tools (e.g. checklist) which could be used as guidance when buying a new washing machine.
- Industries could develop information systems on the washing machine that promotes the extension of the maximal laundry waiting time (e.g. washing frequency tracker, sticker/dosing ball that changes color when used too frequently.
- Detergent manufacturers could develop products that encourage a longer usage of textiles.

8 References

AISE (2008) A.I.S.E Survey - Laundry and cleaning habits study, Insites 2008

AISE (2011) A.I.S.E Survey - Laundry and cleaning habits study, Insites 2011

AISE (2013) The case for the "A.I.S.E low temperature washing" initiative: Substantiation dossier June 2013. AISE, Brussels.

Alders, M. P. & Manting, D. (2001) Household scenarios for the European Union, 1995-2025. *Genus***,** 17-47.

Arild, A.-H., Brusdal, R., Halvorsen-Gunnarsen, J., Terpstra, P. M. & Van Kessel, I. A. (2003) *An investigation of domestic laundry in Europe: habits, hygiene and technical performance*. SIFO, Statens Institutt for Forbruksforskning, Oslo.

Berkholz, P., Brückner, A., Kruschwitz, A. & Stamminger, R. (2007) Definition und Ermittlung verhaltensabhängiger Energieeinsparpotentiale beim Betrieb elektrischer Haushaltswaschmaschinen. Research report Uni Bonn for Bundesministerium für Wirtschaft und Technologie BMWI-Projektnummer: 86/05 Shaker-Verlag, Aachen.(ISBN–978-3-8322-6333-1).

Bertoldi, P. & Atanasiu, B. (2007) Electricity consumption and efficiency trends in the enlarged European Union. IES–JRC. European Union.

Bertoldi, P., Hirl, B. & Labanca, N. (2012) Energy Efficiency Status Report 2012. *European Commission, JRC, Scientific and Policy Reports*, **136**.

Breidenich, C., Magraw, D., Rowley, A. & Rubin, J. W. (1998) The Kyoto protocol to the United Nations framework convention on climate change. *American Journal of International Law***,** 315-331.

Change (1990) Climate change: The IPCC scientific assessment. *Cambridge, Mass*.

Commission, E. (2011) A Roadmap for moving to a competitive low carbon economy in 2050 *(ed. by Commission, E.). Brussels.*

de Almeida, A., Fonseca, P., Schlomann, B., Feilberg, N. & Ferreira, C. (2006) Residential monitoring to decrease energy use and carbon emissions in Europe. In International Energy Efficiency in Domestic Appliances & Lighting Conference.

Dworak, T., Berglund, M., Laaser, C., Strosser, P., Roussard, J., Grandmougin, B., Kossida, M., Kyriazopoulou, I., Berbel, J. & Kolberg, S. (2007) EU Water saving potential (Part 1–Report). *Ecologic-Institute for International and European Environmental Policy***,** 900-949.

EEA (2010) *The European Environment: State and Outlook 2010: Synthesis*. European Environment Agency.

Eurostat (2013) "Population structure and ageing" - Statistics Explained, Retrived from: http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Population_projections [Last accesed: 20.03.2014].

ForumWaschen (2013) Aktionstag - Nachhaltiges (Ab-)Waschen [Online]. Available: http://forum-waschen.de/tl_files/content/pdf-waschen-abwaschen-reinigen/Faltblatt-Nachhaltiges-waschen-13.pdf [Last accessed 16.12. 2013].

Hloch, H.-G., Krüßmann, H., Puchta, R. & Stübler, E. (1989) *Reinigung und Pflege von Textilien im Haushalt*. Verlag Neuer Merkur, Muenchen.

Icha, P. (2013) Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2012. *Climate Change, Umweltbundesamt,* 07/2013.

Jakobi, G. & Löhr, A. (1987) *Detergents and textile washing: principles and practice*. VCH Publishers, New York.

Janczak, F., Stamminger, R., Nickel, D. & Speckmann, H.-D. (2010) Energy savings by low temperature washing. *SÖFW-Journal,* **136,** 75.

Järvi, P. & Paloviita, A. (2007) Product-related information for sustainable use of laundry detergents in Finnish households. *Journal of Cleaner Production,* **15,** 681-689.

Jungbluth, N., (2006) Vergleich der Umweltbelastungen von Hahnenwasser und Mineralwasser. *Gas Wasser Abwasser,* **3,** 215-219.

Kruschwitz, A., Karle, A., Schmitz, A. and Stamminger, R., (2014) *Consumer laundry practices in Germany*, in *International Journal of Consumer Studies*. 2014. p. 265-277. DOI: 10.1111/ijcs.12091

Kutsch, T., Piorkowsky, M.-B. & Schätzke, M. (1997) *Einführung in die Haushaltswissenschaft: Haushaltsökonomie, Haushaltssoziologie, Haushaltstechnik*. UTB.

KyotoProtocol (2013) United Nations Framework Convention on Climate Change [Online]. Available: http://unfccc.int/kyoto_protocol/items/2830.php [Last accessed 20.10. 2013].

Lazarević, M. P. & Vasić, V. (2008) *Mathematical modelling and simulation of a washing machine: a robotic approach*. (ed. by M. Papadrakakis & Topping, B. H. V.). Civil-Comp Press, Stirlingshire, UK.

Mac Namara, C., Gabriele, A., Amador, C. & Bakalis, S. (2012) Dynamics of textile motion in a front-loading domestic washing machine. *Chemical Engineering Science,* **75,** 14-27.

OECD (2011) *The Future of Families to 2030*. OECD Publishing. URL http://www.oecd.org/sti/futures/49093502.pdf [Last accessed on 01.12.2013].

OECD (2013) *Greening Household Behaviour*. OECD Publishing. URL http://www.oecd-ilibrary.org/docserver/download/9713021e.pdf?expires=1396984094&id=id&accname=ocid53021578&checksum=23293813E4CEB3153B061CE448A19A61 [Last accessed on 12.11.2013].

Pakula, C. & Stamminger, R. (2010) Electricity and water consumption for laundry washing by washing machine worldwide. *Energy Efficiency,* **3,** 365-382.

Park, J. & Wassgren, C. R. (2003) Modeling the Dynamics of Fabric in a Rotating Horizontal Drum Using the Discrete Element Method. *Particulate Science and Technology*, **21,** 157-175.

Presutto, M., Stamminger, R., Scaldoni, R., Mebane, W. & Esposito, R. 2007. Preparatory study of Eco-design requirements of EuPs; Lot 14: Domestic washing machines and dishwashers. Available: http://www.atlete.eu/doc/eco/Lot%2014%20Draft%20Final%20Report%20tasks%203-5.pdf [Last accessed on 15. 02. 2014].

Ramasubramanian, M. K. & Tiruthani, K. (2009) A Capacitive Displacement Sensing Technique for Early Detection of Unbalanced Loads in a Washing Machine. *Sensors,* **9,** 9559-9571.

Rüdenauer, I., Gensch, C. O., Grießhammer, R. & Bunke, D. (2005) Integrated environmental and economic assessment of products and processes. *Journal of Industrial Ecology,* **9,** 105-116.

Rüdenauer, I., Grießhammer, R., Götz, K. & Birzle-Harder, B. (2004) PROSA Waschmaschinen. *Produkt-Nachhaltigkeitsanalyse von Waschmaschinen und Waschprozessen, Öko-Institut e. V., Freiburg.* Available: http://ecotopten.info/download/EcoTopTen_Endbericht_Waschen.pdf [Last accessed on 24. 10. 2013].

Shine, K. P., Fuglestvedt, J. S., Hailemariam, K. & Stuber, N. (2005) Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change,* **68,** 281-302.

Sinner, H. (1960) *Über das Waschen mit Haushaltwasmaschinen: in welchem Umfange erleichtern Haushaltwaschmachinen und -geraete das Waeschehaben im Haushalt?* Haus und Heim-Verlag, Hamburg.

Smulders, E., Rybinski, W., Sung, E., Rähse, W., Steber, J., Wiebel, F. & Nordskog, A. (2002) *Laundry detergents*. Wiley-VCH, Weinheim.

Stamminger, R., Barth, A. & Dörr, S. (2005) Old washing machines wash less efficiently and consume more resources. *Hauswirtschaft und Wissenschaft, 3, 2005.*

Stamminger, R., Broil, G., Pakula, C., Jungbecker, H., Braun, M., Rüdenauer, I. & Wendker, C. (2008) Synergy potential of smart appliances. *Report of the Smart-A project.* Available: http://www.smart-a.org/D2.3_Synergy_Potential_of_Smart_Appliances_4.00.pdf [Last accessed on 03.02.2014].

Stamminger, R. & Goerdeler, G. (2007) Aktionstag Nachhaltiges Waschen–Was macht der Verbraucher? *SÖFW-Journal,* **1,** 2-2007.

Terpstra, P. (2001) *Assessment of the cleaning efficiency of domestic washing machines with artificially soiled test cloth*. Springer Berlin Heidelberg.

Vaughn, T. H., Vittone Jr, A. & Bacon, L. R. (1941) Properties of detergent solutions. *Industrial & Engineering Chemistry,* **33,** 1011-1019. URL http://pubs.acs.org/action/showCitFormats?doi=10.1021%2Fie50380a011 [Last accessed on 06.08.2013].

VHK (2013) "Omnibus" Review Study on Cold Appliances, Washing Machines, Dishwashers, Washer-Dryers, Lighting, Set-top Boxes and Pumps. [DRAFT INTERIM REPORT]. [Last accessed on 24. 10. 2013].

Wagner, G. (2011) *Waschmittel-Chemie, Umwelt, Nachhaltigkeit*. 4. Auflage. Wiley-VCH, Weinheim.

Ward, D. (2000) Modelling of a Horizontal-axis Domestic Washing Machine. *Journal of The Textile Institute,* **91,** 207-234.

9 Abbreviations

°C	Degree celsius
ca.	circa
e.g.	exempli gratia
et al.	et alteri
g	Gramm
h	Hour
Hz	Hertz
i.e.	Id est
kg	Kilogram
kWh	Kilowatt-hour
L	Liter
mg	Milligramm
min	Minute
MLWT	Maximal laundry waiting time
mmol / L	Millimol per liter
p.	Page
resp.	Respectively
s	Second
V	Volt
W	Watt
WM	Washing machine
WMRC	Washing machine rated capacity
$\bar{x}$	Arithmetic mean

10 List of figures

11 List of tables

Appendix

12 Appendix

12.1 Washing machine tests data

Table 11-1: Indesit IWB 5125) 5 kg rated capacity

Load size in kg	Detergent dosage in g	Energy consumption in kWh	Energy consumption in main wash in	Water consumption in L	Water consumption main wash in L	Water consumption rinse cycle in L	Duration spinning phase in min	Duration main wash in min	Washing temperature in °C	Washing Performance Index
5,00	50	0,42	0,31	63,7	15,5	48,2	29	41	30	0,81
5,00	50	0,82	0,73	40,8	16,6	24,3	39	84	40	0,91
5,00	50	0,94	0,85	39,5	16,5	23,0	21	84	60	0,94
5,00	100	0,43	0,34	64,0	16,5	47,5	18	41	30	0,87
5,00	100	0,80	0,71	40,5	16,8	23,7	16	84	40	0,98
5,00	100	0,95	0,86	40,8	17,1	23,8	16	83	60	1,00
5,00	150	0,45	0,34	64,4	16,1	48,4	17	41	30	0,90
5,00	150	0,79	0,70	40,4	16,7	23,8	16	83	40	1,02
5,00	150	0,92	0,84	38,6	17,0	21,6	16	83	60	1,04
3,75	42,5	0,40	0,30	58,7	13,6	45,1	17	40	30	0,82
3,75	42,5	0,74	0,65	36,3	14,5	21,8	16	83	40	0,93
3,75	42,5	0,94	0,85	36,9	13,8	23,1	16	82	60	0,97
3,75	85	0,39	0,30	58,2	13,5	44,7	16	40	30	0,90
3,75	85	0,73	0,64	35,8	14,3	21,5	16	82	40	1,01
3,75	85	0,91	0,83	35,7	14,0	21,6	16	82	60	1,04
3,75	127,5	0,41	0,31	58,6	13,7	44,9	16	39	30	0,94
3,75	127,5	0,68	0,60	34,9	14,1	20,9	16	82	40	1,04
3,75	127,5	0,90	0,82	33,3	14,4	18,9	19	83	60	1,08
2,50	35	0,36	0,28	54,0	11,3	42,6	17	38	30	0,85
2,50	35	0,67	0,59	30,8	12,1	18,8	16	81	40	0,96
2,50	35	0,88	0,80	30,6	11,4	19,2	16	81	60	0,98
2,50	70	0,35	0,26	53,9	11,2	42,7	16	38	30	0,92
2,50	70	0,62	0,55	29,7	11,2	18,5	16	81	40	1,02
2,50	70	0,92	0,84	30,2	11,5	18,6	15	81	60	1,07
2,50	105	0,34	0,25	52,9	10,9	42,1	16	38	30	0,96
2,50	105	0,65	0,57	30,5	11,5	18,9	16	81	40	1,07
2,50	105	0,91	0,83	30,2	11,5	18,7	15	81	60	1,13
1,25	27,5	0,30	0,21	46,3	7,7	38,6	17	37	30	0,91
1,25	27,5	0,54	0,46	23,0	8,7	14,4	15	80	40	1,01
1,25	27,5	0,79	0,72	23,3	8,3	15,0	15	81	60	1,05

1,25	55	0,31	0,22	47,3	7,7	39,7	16	37	30	0,98
1,25	55	0,56	0,48	22,8	8,1	14,7	15	81	40	1,08
1,25	55	0,76	0,68	22,3	8,4	13,9	16	81	60	1,13
1,25	82,5	0,30	0,22	45,0	7,5	37,5	16	36	30	0,92
1,25	82,5	0,53	0,46	23,9	8,8	15,1	21	81	40	1,12
1,25	82,5	0,75	0,68	21,6	8,0	13,6	19	81	60	1,17
0,00	0	0,23	0,16	38,6	5,3	33,4	16	35	30	
0,00	0	0,38	0,32	16,7	5,7	11,0	25	80	40	
0,00	0	0,54	0,48	16,3	5,8	10,4	15	81	60	

Table 11-2: Miele W1514WPS, 5 kg rated capacity

Load size in kg	**Detergent dosage in g**	**Energy consumption in kWh**	**Energy consumption in main wash in**	**Water consumption in L**	**Water consumption main wash in L**	**Water consumption rinse cycle in L**	**Duration spinning phase**	**Duration main wash in min**	**Washing temperature in**	**Washing Performance Index**
5,00	50	0,29	0,20	42,8	13,1	29,7	8	52	30	0,93
5,00	50	0,31	0,21	53,0	13,1	39,9	10	71	30	0,88
5,00	50	0,46	0,36	51,9	12,7	39,2	9	71	40	0,95
5,00	50	0,79	0,69	40,8	12,3	28,5	9	63	60	0,98
5,00	100	0,36	0,25	47,8	13,1	34,7	9	71	30	0,99
5,00	100	0,32	0,22	54,6	14,4	40,2	9	71	30	1,00
5,00	100	0,44	0,36	44,2	13,4	30,8	8	52	40	1,02
5,00	100	0,45	0,35	53,0	13,3	39,7	9	71	40	1,00
5,00	100	0,79	0,70	40,8	12,8	28,0	9	63	60	1,06
5,00	150	0,27	0,19	39,8	13,2	26,6	8	52	30	1,01
5,00	150	0,31	0,21	54,3	14,2	40,1	10	71	30	0,97
5,00	150	0,50	0,39	49,8	12,9	36,9	9	71	40	1,06
5,00	150	0,79	0,71	40,5	13,0	27,5	9	63	60	1,13
3,75	42,5	0,22	0,14	32,5	9,7	22,8	8	52	30	0,89
3,75	42,5	0,34	0,27	35,1	11,0	24,1	8	52	40	0,93
3,75	42,5	0,65	0,57	39,6	10,8	28,8	8	52	60	0,97
3,75	85	0,21	0,13	39,5	11,0	28,5	8	52	30	0,95
3,75	85	0,37	0,27	39,6	10,7	28,9	8	52	40	1,00
3,75	85	0,66	0,59	40,4	11,0	29,4	8	52	60	1,05
3,75	127,5	0,23	0,15	39,8	11,5	28,3	8	52	30	1,00
3,75	127,5	0,35	0,27	39,9	11,0	28,9	8	52	40	1,02
3,75	127,5	0,67	0,60	39,4	10,9	28,5	8	52	60	1,12
2,50	35	0,21	0,14	31,7	9,3	22,4	8	52	30	0,94
2,50	35	0,38	0,30	34,4	10,6	23,8	8	52	40	0,98
2,50	35	0,70	0,62	36,7	10,3	26,4	8	52	60	1,03

2,50	70	0,24	0,16	34,1	10,6	23,5	8	52	30	1,00
2,50	70	0,38	0,31	33,9	10,6	23,3	8	52	40	1,05
2,50	70	0,72	0,64	37,5	11,0	26,5	8	52	60	1,12
2,50	105	0,23	0,15	32,5	9,7	22,8	8	52	30	1,04
2,50	105	0,35	0,27	32,9	10,2	22,7	8	52	40	1,08
2,50	105	0,69	0,62	35,8	10,1	25,7	8	52	60	1,17
1,25	27,5	0,17	0,11	20,2	6,7	13,5	5	52	30	0,98
1,25	27,5	0,25	0,19	19,8	6,5	13,3	5	52	40	1,02
1,25	27,5	0,49	0,43	20,2	6,4	13,8	5	52	60	1,06
1,25	55	0,17	0,10	20,0	6,8	13,2	6	52	30	1,05
1,25	55	0,26	0,20	19,7	6,5	13,2	5	52	40	1,01
1,25	55	0,49	0,43	19,7	6,5	13,2	5	52	60	1,14
1,25	82,5	0,17	0,10	25,2	6,4	18,8	6	52	30	1,08
1,25	82,5	0,14	0,12	22,2	7,6	14,6	6	52	30	1,08
1,25	82,5	0,26	0,20	19,4	8,4	11,0	6	52	40	1,13
1,25	82,5	0,47	0,41	18,6	6,2	12,4	6	52	60	1,19
0,00	0	0,16	0,11	21,4	7,3	14,1	6	52	30	
0,00	0	0,25	0,20	21,2	7,3	13,9	6	52	40	
0,00	0	0,46	0,42	21,4	7,5	13,9	6	52	60	

Table 11-3: BOSCH maxx 6 Eco Wash, 6 kg rated capacity

Load size in kg	**Detergent dosage in g**	**Energy consumption in kWh**	**Energy consumption in main wash in**	**Water consumption in L**	**Water consumption main wash in L**	**Water consumption rinse cycle in L**	**Duration spinning phase in min**	**Duration main wash in min**	**Washing temperature in °C**	**Washing Performance Index**
6,00	56	0,26	0,16	53,1	16,4	36,7	15	19	30	0,71
6,00	56	0,39	0,29	56,4	15,8	40,6	13	23	40	0,74
6,00	56	0,91	0,82	52,1	15,6	36,5	13	41	60	0,82
6,00	112	0,23	0,14	52,5	16,8	35,7	13	18	30	0,76
6,00	112	0,42	0,32	55,2	15,9	39,3	13	24	40	0,81
6,00	112	0,90	0,81	51,6	15,3	36,3	15	41	60	0,90
6,00	168	0,21	0,12	50,9	14,9	36,0	13	18	30	0,75
6,00	168	0,41	0,32	50,7	16,1	34,6	13	24	40	0,83
6,00	168	0,88	0,79	54,1	15,7	38,4	13	41	60	0,96
4,50	47	0,27	0,18	49,3	14,7	34,6	15	19	30	0,79
4,50	47	0,53	0,44	50,6	14,9	35,7	13	28	40	0,84
4,50	47	0,92	0,83	48,2	13,6	34,6	13	42	60	0,90
4,50	94	0,24	0,15	49,5	15,1	34,4	12	17	30	0,83
4,50	94	0,53	0,44	51,7	15,2	36,5	13	28	40	0,92

4,50	94	0,90	0,82	47,8	13,5	34,3	13	42	60	0,98
4,50	141	0,24	0,15	49,2	14,9	34,3	13	19	30	0,87
4,50	141	0,51	0,42	49,5	15,2	34,3	13	28	40	0,94
4,50	141	0,94	0,85	49,0	14,0	35,0	13	43	60	1,04
3,00	38	0,27	0,18	45,8	11,7	34,1	13	19	30	0,79
3,00	38	0,46	0,37	46,6	12,2	34,4	12	26	40	0,86
3,00	38	0,78	0,69	45,4	10,8	34,6	13	37	60	0,93
3,00	76	0,29	0,19	45,9	11,9	34,0	16	20	30	0,87
3,00	76	0,44	0,35	46,3	11,8	34,5	13	25	40	0,92
3,00	76	0,81	0,73	45,8	11,2	34,6	13	37	60	1,01
3,00	114	0,24	0,15	46,4	12,2	34,2	13	18	30	0,91
3,00	114	0,47	0,39	46,4	12,0	34,4	13	27	40	0,96
3,00	114	0,75	0,67	45,4	10,7	34,7	12	36	60	1,07
1,50	29	0,24	0,14	43,0	8,6	34,4	14	18	30	0,82
1,50	29	0,40	0,30	43,0	8,7	34,3	12	24	40	0,93
1,50	29	0,66	0,57	42,7	8,3	34,4	14	33	60	0,97
1,50	58	0,24	0,14	43,5	9,1	34,4	16	18	30	0,91
1,50	58	0,39	0,30	43,6	9,0	34,6	14	24	40	0,97
1,50	58	0,64	0,55	42,7	8,2	34,5	12	33	60	1,04
1,50	87	0,24	0,14	43,4	8,9	34,5	16	17	30	0,93
1,50	87	0,38	0,30	30,0	9,1	20,9	15	24	40	0,99
1,50	87	0,42	0,32	42,4	8,9	33,5	14	24	40	1,09
1,50	87	0,63	0,54	42,6	8,1	34,5	13	32	60	1,00
0,00	0	0,18	0,11	22,9	5,6	17,3	12	17	30	
0,00	0	0,27	0,20	22,8	5,5	17,3	12	21	40	
0,00	0	0,43	0,36	22,0	4,7	17,3	12	27	60	

Table 11-4: AEG Öko Lavamat 76850, 7 kg rated capacity

Load size in kg	**Detergent dosage in g**	**Energy consumption in kWh**	**Energy consumption in main wash in**	**Water consumption in L**	**Water consumption main wash in L**	**Water consumption rinse cycle in L**	**Duration spinning phase in min**	**Duration main wash in min**	**Washing temperature in °C**	**Washing Performance Index**
7,00	62	0,42	0,28	59,8	18,2	41,6	17	63	30	0,82
7,00	62	0,63	0,50	62,1	19,4	42,7	14	67	40	0,88
7,00	62	1,26	1,12	62,9	19,6	43,3	14	89	60	0,90
7,00	124	0,42	0,26	59,2	18,0	41,2	23	62	30	0,86
7,00	124	0,73	0,61	61,1	19,4	41,7	17	73	40	0,96
7,00	124	1,16	1,03	61,7	18,2	43,5	19	87	60	1,03

7,00	186	0,44	0,31	60,0	18,2	41,8	13	65	30	0,92
7,00	186	0,66	0,53	60,7	18,1	42,6	17	70	40	1,00
7,00	186	1,20	1,07	61,2	18,1	43,1	14	88	60	1,06
5,25	51,5	0,44	0,32	60,4	18,1	42,3	14	66	30	0,89
5,25	51,5	0,80	0,66	60,7	18,2	42,5	16	75	40	0,93
5,25	51,5	1,24	1,12	62,1	18,1	44,0	15	90	60	0,96
5,25	103	0,50	0,36	62,6	18,7	43,9	17	67	30	0,96
5,25	103	0,73	0,58	61,7	17,9	43,8	16	74	40	1,01
5,25	103	1,23	1,11	62,1	18,2	43,9	18	91	60	1,06
5,25	154,5	0,46	0,33	61,5	18,0	43,5	14	65	30	1,01
5,25	154,5	0,74	0,62	61,9	18,0	43,9	18	75	40	1,04
5,25	154,5	1,22	1,09	62,0	18,1	43,9	14	89	60	1,11
3,50	41	0,42	0,29	55,2	14,5	40,7	18	67	30	0,91
3,50	41	0,60	0,47	46,5	11,7	34,8	15	68	40	0,95
3,50	41	0,69	0,57	55,8	14,5	41,3	14	75	40	0,97
3,50	41	0,86	0,74	44,3	11,5	32,8	14	75	60	0,97
3,50	41	1,04	0,91	53,0	13,6	39,4	17	81	60	1,02
3,50	82	0,42	0,29	56,7	14,6	42,1	17	64	30	0,97
3,50	82	0,70	0,57	54,9	14,7	40,2	16	76	40	1,03
3,50	82	0,92	0,79	47,0	11,6	35,4	21	77	60	1,00
3,50	82	1,13	1,00	54,4	14,6	39,8	17	87	60	1,01
3,50	123	0,48	0,31	56,4	14,5	41,9	30	66	30	1,02
3,50	123	0,72	0,60	56,3	14,6	41,7	14	76	40	1,07
3,50	123	0,91	0,79	46,2	11,8	34,4	14	75	60	1,11
3,50	123	1,07	0,93	53,8	13,9	39,9	16	82	60	1,14
1,75	30,5	0,41	0,29	40,6	11,7	28,9	17	64	30	0,95
1,75	30,5	0,62	0,50	41,4	11,9	29,5	15	71	40	0,98
1,75	30,5	0,98	0,86	41,4	12,0	29,4	15	79	60	1,01
1,75	61	0,37	0,24	40,7	11,8	28,9	15	62	30	1,01
1,75	61	0,61	0,48	41,3	11,8	29,5	16	70	40	1,05
1,75	61	0,97	0,85	41,9	12,0	29,9	14	78	60	1,11
1,75	91,5	0,38	0,26	40,1	11,7	28,4	14	63	30	1,05
1,75	91,5	0,60	0,48	41,2	11,7	29,5	14	70	40	1,10
1,75	91,5	0,99	0,87	41,8	12,0	29,8	14	79	60	1,16
0,00	0	0,38	0,27	33,5	12,2	21,3	14	65	30	
0,00	0	0,58	0,48	32,8	12,1	20,7	14	71	40	
0,00	0	0,95	0,85	32,6	12,2	20,4	14	79	60	

Table 11-5: Bauknecht WA UNIQ 714FLD, 7kg rated capacity

Load size in kg	**Detergent dosage in g**	**Energy consumption in kWh**	**Energy consumption in main wash in**	**Water consumption in L**	**Water consumption main wash in L**	**Water consumption rinse cycle in L**	**Duration spinning phase in min**	**Duration main wash in min**	**Washing temperature in °C**	**Washing Performance Index**
7,00	62	0,44	0,28	101,1	19,3	81,8	21	45	30	0,84
7,00	62	0,63	0,46	105,2	20,1	85,0	20	44	40	0,84
7,00	62	0,98	0,87	53,3	17,5	35,8	22	87	60	0,99
7,00	124	0,41	0,25	99,5	19,1	80,4	23	45	30	0,85
7,00	124	0,53	0,36	96,9	18,8	78,1	18	45	40	0,90
7,00	124	0,97	0,86	56,6	17,8	38,8	19	87	60	1,04
7,00	186	0,45	0,28	104,0	19,9	84,1	23	45	30	0,89
7,00	186	0,59	0,42	104,1	19,9	84,2	19	44	40	0,92
7,00	186	1,01	0,90	54,5	17,6	36,9	17	88	60	1,12
5,25	51,5	0,39	0,26	68,4	17,3	51,2	19	76	30	0,84
5,25	51,5	0,62	0,49	67,4	16,2	51,2	24	77	40	0,91
5,25	51,5	1,04	0,93	53,0	16,2	36,8	17	87	60	0,96
5,25	103	0,37	0,24	65,4	16,5	49,0	24	75	30	0,92
5,25	103	0,61	0,49	65,9	15,8	50,1	26	77	40	0,98
5,25	103	1,04	0,93	54,4	16,2	38,2	16	87	60	1,04
5,25	154,5	0,41	0,28	66,8	16,6	50,2	21	76	30	0,98
5,25	154,5	0,65	0,52	66,8	16,5	50,3	32	78	40	1,04
5,25	154,5	1,04	0,93	52,9	15,2	37,7	26	86	60	1,11
3,50	41	0,47	0,34	57,9	13,8	44,1	20	75	30	0,91
3,50	41	0,64	0,52	57,7	14,0	43,6	18	77	40	0,96
3,50	41	1,02	0,90	43,1	13,7	29,3	18	85	60	0,99
3,50	82	0,46	0,34	57,9	13,8	44,1	22	76	30	0,99
3,50	82	0,65	0,53	56,9	13,7	43,2	19	77	40	1,01
3,50	82	1,04	0,91	42,9	13,7	29,3	23	84	60	1,08
3,50	123	0,45	0,32	57,1	13,8	43,3	18	75	30	1,02
3,50	123	0,65	0,52	56,4	13,7	42,7	20	77	40	1,06
3,50	123	1,05	0,94	45,4	13,8	31,6	24	84	60	1,14
1,75	30,5	0,51	0,40	56,2	13,6	42,6	26	75	30	0,97
1,75	30,5	0,71	0,59	56,3	13,4	42,9	26	76	40	1,02
1,75	30,5	1,07	0,97	43,0	13,7	29,4	18	83	60	1,01
1,75	61	0,50	0,39	56,6	13,6	43,0	18	74	30	1,05
1,75	61	0,72	0,60	57,1	13,7	43,4	21	76	40	1,06
1,75	61	1,08	0,97	42,5	13,8	28,7	19	83	60	1,12
1,75	91,5	0,50	0,38	56,5	13,7	42,8	24	75	30	1,08

1,75	91,5	0,72	0,60	56,7	13,5	43,2	19	76	40	1,12
1,75	91,5	1,06	0,96	42,4	13,5	28,9	16	83	60	1,17
0,00	0	0,20	0,14	23,2	6,6	16,6	9	28	30	
0,00	0	0,29	0,24	22,9	6,6	16,3	9	28	40	
0,00	0	0,47	0,42	23,0	6,6	16,4	9	28	60	

Table 11-6: BoschLogix8, 8kg rated capacity

Load size in kg	**Detergent dosage in g**	**Energy consumption in kWh**	**Energy consumption in main wash in kWh**	**Water consumption in L**	**Water consumption main wash in L**	**Water consumption rinse cycle in L**	**Duration spinning phase in min**	**Duration main wash in min**	**Washing temperature in °C**	**Washing Performance Index**
8,00	68	0,26	0,13	78,5	19,8	58,7	11	87	30	0,79
8,00	68	0,76	0,66	79,4	20,8	58,6	11	100	40	0,87
8,00	68	1,00	0,89	78,4	19,8	58,6	12	107	60	0,88
8,00	136	0,30	0,20	78,4	19,8	58,6	12	87	30	0,86
8,00	136	0,78	0,68	79,6	20,9	58,7	12	100	40	0,96
8,00	136	0,99	0,89	78,4	19,8	58,6	12	107	60	0,99
8,00	204	0,29	0,18	78,6	19,8	58,8	11	87	30	0,90
8,00	204	0,77	0,67	79,6	20,9	58,7	11	100	40	0,97
8,00	204	1,15	1,06	78,6	19,9	58,7	12	107	60	1,06
6,00	56	0,35	0,25	78,5	19,9	58,6	12	86	30	0,89
6,00	56	0,82	0,72	79,4	20,9	58,5	11	100	40	0,95
6,00	56	1,24	1,12	78,4	19,8	58,6	11	107	60	0,97
6,00	112	0,32	0,22	78,4	19,8	58,6	11	87	30	0,95
6,00	112	0,81	0,71	79,5	20,9	58,6	12	100	40	1,01
6,00	112	1,22	1,10	78,4	19,8	58,6	16	107	60	1,06
6,00	168	0,32	0,21	78,4	19,8	58,6	12	87	30	0,98
6,00	168	0,81	0,71	79,4	20,9	58,5	12	100	40	1,06
6,00	168	1,23	1,13	78,4	19,8	58,6	11	107	60	1,11
4,00	44	0,26	0,15	58,6	14,1	44,5	12	71	30	0,89
4,00	44	0,62	0,53	58,6	14,1	44,5	11	83	40	0,96
4,00	44	0,89	0,80	58,6	14,1	44,5	12	92	60	1,00
4,00	88	0,22	0,13	58,6	14,1	44,5	11	72	30	0,97
4,00	88	0,63	0,54	58,6	14,1	44,5	11	83	40	1,03
4,00	88	0,92	0,82	58,6	14,1	44,5	13	92	60	1,07
4,00	132	0,24	0,14	58,6	14,1	44,5	12	72	30	0,99
4,00	132	0,60	0,50	58,6	14,1	44,5	13	83	40	1,07
4,00	132	0,92	0,83	58,6	14,1	44,5	14	92	60	1,14
2,00	32	0,29	0,20	49,2	11,5	37,7	12	62	30	0,95

2,00	32	0,51	0,42	49,2	11,5	37,7	11	73	40	1,00
2,00	32	0,81	0,72	49,2	11,5	37,7	12	82	60	1,04
2,00	64	0,27	0,17	49,1	11,5	37,6	13	62	30	1,00
2,00	64	0,51	0,42	49,2	11,5	37,7	12	72	40	1,06
2,00	64	0,84	0,74	49,2	11,5	37,7	12	82	60	1,11
2,00	96	0,27	0,18	49,2	11,5	37,7	11	62	30	1,03
2,00	96	0,58	0,48	49,2	11,5	37,7	15	72	40	1,10
2,00	96	0,83	0,73	49,2	11,5	37,7	13	82	60	1,15
0,00	0	0,17	0,11	22,9	6,3	16,6	11	42	30	
0,00	0	0,34	0,28	22,9	6,4	16,5	11	53	40	
0,00	0	0,47	0,41	22,9	6,3	16,6	11	62	60	

Table 11-7: Haier HWF1481, 8 kg rated capacity

Load size in kg	**Detergent dosage in g**	**Energy consumption in kWh**	**Energy consumption in main wash in kWh**	**Water consumption in L**	**Water consumption main wash in L**	**Water consumption rinse cycle in L**	**Duration spinning phase in min**	**Duration main wash in min**	**Washing temperature in °C**	**Washing Performance Index**
8,00	68	0,26	0,16	63,2	21,1	42,1	15	61	30	0,77
8,00	68	0,41	0,33	65,5	22,0	43,5	21	61	40	0,82
8,00	68	1,25	1,16	64,2	20,8	43,4	25	73	60	0,90
8,00	136	0,22	0,16	63,5	21,1	42,4	16	61	30	0,88
8,00	136	0,44	0,36	63,0	21,2	41,8	23	61	40	0,91
8,00	136	1,26	1,20	59,9	20,5				60	1,00
8,00	136	1,32	1,25	64,1	21,4				60	1,03
8,00	136	1,26	1,15	59,9	21,0				60	1,00
8,00	204	0,21	0,14	65,4	22,4	43,1	17	61	30	0,89
8,00	204	0,48	0,40	61,2	20,9	40,3	16	61	40	0,96
8,00	204	1,18	1,10	64,3	21,5	42,8	18	72	60	1,04
6,00	56	0,26	0,18	59,1	18,6	40,4	15	61	30	0,83
6,00	56	0,56	0,49	60,1	18,9	41,2	14	61	40	0,88
6,00	56	1,15	1,08	57,3	17,5	39,8	15	72	60	0,94
6,00	112	0,28	0,19	60,3	18,9	41,4	18	61	30	0,91
6,00	112	0,60	0,52	58,7	19,2	39,5	15	61	40	0,95
6,00	112	1,15	1,07	61,2	17,5	43,7	21	72	60	1,01
6,00	168	0,29	0,21	59,3	19,6	39,7	16	61	30	0,94
6,00	168	0,62	0,55	61,4	19,8	41,5	15	61	40	1,00
6,00	168	1,15	1,08	59,1	18,0	41,1	24	72	60	1,09
4,00	44	0,27	0,19	51,9	14,1	37,8	16	61	30	0,87
4,00	44	0,45	0,38	52,0	14,1	37,9	14	61	40	0,91

4,00	44	1,08	1,00	53,2	15,1	38,1	17	72	60	0,98
4,00	88	0,29	0,20	54,1	15,9	38,2	14	61	30	0,95
4,00	88	0,50	0,42	53,4	15,4	38,0	15	61	40	0,99
4,00	88	1,06	0,98	54,1	15,0	39,1	15	72	60	1,06
4,00	132	0,24	0,17	51,9	15,1	36,9	14	61	30	0,99
4,00	132	0,44	0,37	52,2	15,5	36,8	15	61	40	1,01
4,00	132	0,98	0,91	54,7	16,0	38,6	17	72	60	1,11
2,00	32	0,25	0,17	38,4	10,5	27,9	26	61	30	0,92
2,00	32	0,41	0,34	38,4	10,6	27,8	19	61	40	0,96
2,00	32	0,84	0,77	38,2	10,8	27,4	14	73	60	1,02
2,00	64	0,24	0,16	37,7	10,1	27,6	24	61	30	0,98
2,00	64	0,41	0,33	38,2	10,3	27,9	14	61	40	1,01
2,00	64	0,80	0,72	38,1	10,4	27,8	14	72	60	1,09
2,00	96	0,25	0,17	38,0	10,6	27,4	20	62	30	1,06
2,00	96	0,39	0,32	37,1	10,2	27,0	13	61	40	1,12
2,00	96	0,82	0,75	38,2	10,6	27,6	14	72	60	1,18
0,00	0	0,20	0,14	38,6	7,5	31,1	26	61	30	
0,00	0	0,32	0,26	38,3	7,5	30,9	16	61	40	
0,00	0	0,60	0,54	38,6	7,6	31,0	21	72	60	

Table 11-8: INDESIT PWE 8168W, 8kg rated capacity

Load size in kg	Detergent dosage in g	Energy consumption in kWh	Energy consumption in main wash in kWh	Water consumption in L	Water consumption main wash in L	Water consumption rinse cycle in L	Duration spinning phase in min	Duration main wash in min	Washing temperature in °C	Washing Performance Index
8,00	68	0,47	0,35	70,6	23,7	46,9	20	34	30	0,75
8,00	68	1,15	1,03	73,5	25,9	47,6	19	161	40	0,93
8,00	68	1,33	1,21	72,1	25,3	46,8	22	161	60	0,96
8,00	136	0,47	0,34	73,2	24,2	49,0	22	42	30	0,82
8,00	136	1,10	0,98	74,2	25,5	48,7	19	161	40	1,02
8,00	136	1,34	1,23	74,2	27,4	46,8	19	161	60	1,04
8,00	204	0,43	0,32	70,7	24,1	46,6	18	41	30	0,87
8,00	204	1,10	1,00	72,5	26,0	46,5	21	161	40	1,08
8,00	204	1,33	1,21	71,1	24,8	46,3	33	161	60	1,09
6,00	56	0,38	0,29	63,4	20,2	43,2	19	31	30	0,76
6,00	56	1,10	0,97	67,3	23,0	44,3	20	162	40	0,97
6,00	56	1,33	1,23	64,4	21,4	43,0	20	161	60	0,99
6,00	112	0,43	0,32	63,1	21,0	42,1	19	41	30	0,87
6,00	112	1,03	0,93	65,9	22,3	43,5	22	161	40	1,06
6,00	112	1,34	1,24	66,4	22,2	44,3	19	161	60	1,09

6,00	168	0,42	0,31	63,6	20,9	42,6	21	41	30	0,91
6,00	168	1,04	0,93	65,6	22,2	43,4	19	161	40	1,10
6,00	168	1,34	1,24	66,6	22,5	44,1	19	161	60	1,14
4,00	44	0,36	0,25	54,2	15,4	38,8	19	26	30	0,79
4,00	44	0,88	0,78	56,6	17,3	39,3	21	160	40	0,97
4,00	44	1,22	1,11	57,6	17,9	39,7	19	155	60	1,01
4,00	88	0,33	0,23	53,9	15,6	38,3	19	26	30	0,85
4,00	88	0,96	0,85	56,5	18,0	38,6	19	160	40	1,05
4,00	88	1,22	1,12	57,0	17,9	39,1	19	156	60	1,10
4,00	132	0,38	0,26	54,8	16,3	38,5	22	26	30	1,09
4,00	132	0,95	0,86	58,2	18,1	40,1	18	161	40	1,14
4,00	132	1,20	1,11	56,6	17,8	38,8	19	156	60	0,88
2,00	32	0,29	0,20	42,2	11,2	31,0	20	22	30	0,81
2,00	32	0,74	0,64	43,1	12,1	31,0	25	159	40	1,04
2,00	32	0,93	0,84	42,8	12,8	30,1	32	152	60	1,07
2,00	64	0,28	0,19	41,2	11,5	29,7	19	23	30	0,90
2,00	64	0,76	0,67	41,8	12,4	29,4	19	159	40	1,10
2,00	64	0,94	0,84	41,2	12,2	29,0	27	153	60	1,15
2,00	96	0,30	0,21	41,3	11,2	30,1	19	23	30	0,95
2,00	96	0,70	0,60	41,4	11,7	29,8	19	159	40	1,15
2,00	96	0,93	0,84	42,9	12,4	30,4	20	147	60	1,19
0,00	0	0,19	0,11	30,9	6,2	24,7	22	21	30	
0,00	0	0,45	0,38	32,1	7,0	25,1	18	158	40	
0,00	0	0,57	0,49	31,6	6,8	24,8	18	147	60	

Table 11-9: Bauknecht WAB-1210, 11kg rated capacity

Load size in kg	**Detergent dosage in g**	**Energy consumption in kWh**	**Energy consumption in main wash in kWh**	**Water consumption in L**	**Water consumption main wash in L**	**Water consumption rinse cycle in L**	**Duration spinning phase in min**	**Duration main wash in min**	**Washing temperature in °C**	**Washing Performance Index**
11,00	86	0,74	0,59	82,8	25,5	56,7	9	169	30	0,90
11,00	172	0,77	0,56	82,4	25,5	56,3	9	169	30	1,02
11,00	258	0,71	0,56	82,7	25,5	56,3	9	169	30	1,04
8,25	69,5	1,00	0,78	84,0	26,5	57,3	9	167	30	0,97
8,25	139	0,97	0,78	83,2	25,6	54,8	8	167	30	1,04
8,25	208,5	0,94	0,78	83,2	25,5	56,8	8	167	30	1,07
5,50	53	0,67	0,55	55,0	16,8	37,4	8	173	30	0,97
5,50	106	0,63	0,50	55,0	17,0	37,5	8	173	30	1,04

5,50	159	0,68	0,54	55,0	16,4	36,9	8	173	30	1,08
2,75	36,5	0,50	0,40	42,1	12,3	28,3	8	124	30	0,96
2,75	73	0,56	0,46	45,8	13,6	30,9	8	124	30	1,07
2,75	109,5	0,51	0,41	42,7	12,7	28,8	8	124	30	1,13
11,00	86	0,99	0,84	82,9	25,5	56,2	9	173	40	0,96
11,00	172	1,04	0,85	82,4	25,5	56,3	9	173	40	1,03
11,00	258	1,04	0,85	83,3	26,0	56,9	9	173	40	1,08
8,25	69,5	1,35	1,16	83,4	26,1	57,3	8	175	40	0,99
8,25	139	1,31	1,15	82,7	25,7	57,0	8	174	40	1,09
8,25	208,5	1,32	1,16	82,7	25,5	57,2	8	174	40	1,11
5,50	53	0,81	0,68	53,8	16,2	36,4	8	173	40	0,99
5,50	106	0,82	0,69	55,0	16,4	37,0	8	173	40	1,08
5,50	159	0,81	0,69	54,7	16,4	37,2	8	173	40	1,11
2,75	36,5	0,66	0,56	44,6	13,1	44,6	8	124	40	0,97
2,75	73	0,68	0,58	45,4	13,5	30,6	8	124	40	1,08
2,75	109,5	0,66	0,55	44,5	13,0	29,8	8	124	40	1,14
11,00	86	1,44	1,25	82,8	25,5	57,3	8	186	60	0,95
11,00	172	1,33	1,17	82,9	25,5	57,1	9	187	60	1,05
11,00	172	1,38	1,20	82,7	25,5	57,1	9	188	60	1,05
11,00	172	1,38	1,21	82,6	25,5	57,1	9	188	60	1,03
11,00	258	1,35	1,19	82,7	25,4	57,2	9	186	60	1,09
8,25	69,5	1,78	1,53	84,0	26,8	57,9	9	190	60	1,00
8,25	139	1,66	1,50	83,6	26,1	57,5	8	189	60	1,07
8,25	208,5	1,68	1,50	83,3	25,5	57,9	8	189	60	1,14
5,50	86	1,15	1,01	55,7	17,4	38,0			60	0,99
5,50	106	1,12	0,97	54,7	16,4	37,0	8	181	60	1,07
5,50	159	1,04	0,91	53,5	15,3	35,6	8	181	60	1,14
2,75	36,5	1,02	0,91	45,2	13,3	30,6	8	125	60	1,01
2,75	73	1,01	0,92	45,8	13,6	30,9	8	125	60	1,12
2,75	109,5	1,03	0,92	47,4	13,9	31,4	8	125	60	1,18
0,00		1,12	0,97	54,0	15,4	36,4	8	181	60	0,00

12.2 Virtual washing machine MATLAB source code

```
function [ DET, CWmw, CEmw, vektorWASCHKORB] =
Waschmaschine(BETA, WP, TEMP, WMV, MWD, WASCHKORB, m,
WochenCounterGENERAL, RESTLOAD, REG1ODERNOT2, PERSON,
LOADamoountTOTAL,WOCHENLA, n, SZX)
    if TEMP ==30;
WP = .93;
    end
    if TEMP ==40;
```

```
WP = 1;
    end
    if TEMP ==60;
WP = 1.04;
    end
if  WMV ==5;
    if TEMP ==30;
MWD = 48;
    end
    if TEMP ==40;
MWD = 69;
    end
    if TEMP ==60;
MWD = 68;
    end
end
if  WMV ==6;
    if TEMP ==30;
MWD = 50;
    end
    if TEMP ==40;
MWD = 69;
    end
    if TEMP ==60;
MWD = 68;
    end
end
if  WMV ==7;
    if TEMP ==30;
MWD = 65;
    end
    if TEMP ==40;
MWD = 69;
    end
    if TEMP ==60;
MWD = 82;
    end
end
if  WMV ==8;
    if TEMP ==30;
MWD = 68;
    end
    if TEMP ==40;
MWD = 102; % Dauer des hauptwaschganges
    end
    if TEMP ==60;
MWD = 108; % Dauer des hauptwaschganges in minuten in einer
kg waschmaschine
```

```
    end
end
if  WMV ==9;
    if TEMP ==30;
MWD = 120;
    end
    if TEMP ==40;
MWD = 130;
    end
    if TEMP ==60;
MWD = 140;
    end
end
if  WMV ==10;
    if TEMP ==30;
MWD = 140;
    end
    if TEMP ==40;
MWD = 158;
    end
    if TEMP ==60;
MWD = 173;
    end
end
if  WMV ==11;
    if TEMP ==30;
MWD = 156;
    end
    if TEMP ==40;
MWD = 158;
    end
    if TEMP ==60;
MWD = 173;
    end
end
DET=0;
CWmw =0;
CEmw =0;
DET = ((WP - BETA.const.DET)/BETA.det.DET) -
((BETA.temp.DET*TEMP)/BETA.det.DET) -
((BETA.load.DET*WASCHKORB)/BETA.det.DET)  -
((BETA.mwd.DET*MWD)/BETA.det.DET);
if DET<40
    DET = 40;
end
CWmw = BETA.const.WATER + (BETA.load.WATER *WASCHKORB)+
(BETA.wmv.WATER *WMV);
```

```
CEmw = BETA.const.ENERGY + (BETA.temp.ENERGY * TEMP) +
(BETA.water.ENERGY * CWmw) + (BETA.mwd.ENERGY * MWD);
if REG1ODERNOT2 == 2;
RESTLOAD =0;
end
vektorWASCHKORB (1,:) = [n,m,
WochenCounterGENERAL,PERSON,LOADamoountTOTAL,WOCHENLA,
WASCHKORB, TEMP,WMV,MWD, RESTLOAD,WP, DET, CWmw,CEmw,
REG1ODERNOT2, SZX];
end
```

12.3 Virtual washing household MATLAB source code

```
CO2TOTAL=0;
PERSON =0;
myArray = zeros(7,12);
WMV=5;
MAXIMALEWARTEZEITWASCHEN = 0;
SZX=0;
for WMV=5:11;
for PERSON = 1:7;
WochenLA = 4;
Amountof30 = .23;
Amountof40 = .46;
Amountof60 = .31;
LB30 = .5;
LB40 = .7;
LB60 = .9;
MWD30 = 52;
MWD40 = 77;
MWD60 = 84;
BETA.const.DET = 0.8204235;
BETA.temp.DET = 0.002605017;
BETA.load.DET =-0.034011332;
BETA.wmv.DET =-0.000505483;
BETA.mwd.DET =0.001346586;
BETA.det.DET=0.001163081;
BETA.const.WATER =3.949488643;
BETA.load.WATER =1.703739258;
BETA.wmv.WATER =.513236840;
BETA.const.ENERGY =-.85617463;
BETA.temp.ENERGY =.02019412;
BETA.water.ENERGY =.02422291;
BETA.mwd.ENERGY =.00250646;
WP = 1.03;
Weekcounter = 0;
DOS = 52;
```

```
co2water = 0.59;
co2energy = 600;
co2detergent = 2;
LOADamoountTOTAL = PERSON * WochenLA;
WMRECOMENDEDload30 = WMV*LB30;
WMRECOMENDEDload40 = WMV*LB40;
WMRECOMENDEDload60 = WMV*LB60;
WOCHENLA30 = round(LOADamoountTOTAL * Amountof30);
WOCHENLA40 = round(LOADamoountTOTAL * Amountof40);
WOCHENLA60 = round(LOADamoountTOTAL * Amountof60);
WochenCounterGENERAL = 0
m=0;
WASCHKORB= 0;
WASCHKORB30 = 0;
RESTLOAD =0;
TEMP=30;
MWD = MWD30;
WochenCounterREG30 = 0;
WochenCounterNOT30 = 0;
WieoftgewaschenREG30 = 0;
WieoftgewaschenNOT30 = 0;
NOTWASCHGANG = 0;
REG1ODERNOT2 = 0;
DETwaschwoche =0;
CWmwwaschwoche =0;
CEmwwaschwoche =0;
CO2DETwaschwoche = 0;
CO2CWmwwaschwoche =0;
CO2CEmwwaschwoche =0;
CEmwwaschwocheSCHLEIFE=0;
DETwaschwocheSCHLEIFE =0;
CWmwwaschwocheSCHLEIFE = 0;
vektorWASCHKORB1 = zeros (1,17);
for n=1:(DOS);
  REG1ODERNOT2 = 3;
  WochenCounterGENERAL = WochenCounterGENERAL+1;
  Waschkorb30 = WOCHENLA30 + RESTLOAD;
  if Waschkorb30 < WMRECOMENDEDload30 && WochenCounterNOT30 <
MAXIMALEWARTEZEITWASCHEN
  RESTLOAD = Waschkorb30;
  WochenCounterNOT30 = WochenCounterNOT30 +1;
  elseif Waschkorb30 < WMRECOMENDEDload30 &&
WochenCounterNOT30 == MAXIMALEWARTEZEITWASCHEN
      m=m+1;
      WASCHKORB = Waschkorb30;
      REG1ODERNOT2 = 2;
      WOCHENLA = WOCHENLA30;
```

```
      [DET, CWmw, CEmw, vektorWASCHKORB] = Waschmaschine(BETA,
WP, TEMP, WMV, MWD, WASCHKORB, m, WochenCounterGENERAL,
RESTLOAD, REG1ODERNOT2, PERSON, LOADamoountTOTAL,
WOCHENLA,n,SZX);
      vektorWASCHKORB = vertcat(vektorWASCHKORB1,
vektorWASCHKORB);
     vektorWASCHKORB1=vektorWASCHKORB;
      WochenCounterNOT30 = 0;
      NOTWASCHGANG = NOTWASCHGANG+1; % Anzahl der
NOTWaschgägnge
      RESTLOAD =0;
      REG1ODERNOT2 = 0;
  end
  while Waschkorb30 >= WMRECOMENDEDload30  %Reguläres Waschen
     m=m+1;
     RESTLOAD = Waschkorb30 - WMRECOMENDEDload30;
     WASCHKORB = WMRECOMENDEDload30;
     REG1ODERNOT2 = 1;
     WOCHENLA = WOCHENLA30;
     [DET,CWmw,CEmw, vektorWASCHKORB] = Waschmaschine(BETA,
WP, TEMP, WMV, MWD, WASCHKORB, m, WochenCounterGENERAL,
RESTLOAD,  REG1ODERNOT2, PERSON, LOADamoountTOTAL, WOCHENLA,n,
SZX);
     vektorWASCHKORB = vertcat(vektorWASCHKORB1,
vektorWASCHKORB); %
     vektorWASCHKORB1=vektorWASCHKORB;
     WochenCounterREG30 = WochenCounterREG30 +1;
     Waschkorb30=RESTLOAD;
     WochenCounterNOT30 =0;
     REG1ODERNOT2 = 0;
  end
  vNOTWASCHGANG(n+1,1) =NOTWASCHGANG;
  vWochenCounterGENERAL (n+1,1) = WochenCounterGENERAL;
  if REG1ODERNOT2 == 3;
    DET = 0;
    CWmw =0;
    CEmw =0;
    REG1ODERNOT2=3;
    WASCHKORB=0;
    WOCHENLA =0;
    vektorWASCHKORB=zeros(1,17); %
    vektorWASCHKORB (1,:) = [n, m, WochenCounterGENERAL,
PERSON, LOADamoountTOTAL, WOCHENLA, WASCHKORB, TEMP,WMV,MWD,
RESTLOAD, WP, DET, CWmw, CEmw, REG1ODERNOT2, SZX];
    vektorWASCHKORB2 = vertcat(vektorWASCHKORB1,
vektorWASCHKORB);
    vektorWASCHKORB1=vektorWASCHKORB2;
  end
```

```
end
TEST30 = vektorWASCHKORB1;
vektorWASCHKORB1=zeros(1,17);
```

Acknowledgements

First of all I would like to express my thanks to Prof. Dr. Rainer Stamminger who gave me this exciting topic. His interest in my work, qualified support, swift feedback and many helpful discussions as well as the technical and editorial advices were an important prerequisite for the successful completion of this thesis.

I also would like to thank Prof. Dr. Michael-Burkhard Piorkowsky who agreed to become the second examiner.

Furthermore, I would like to thank to Henkel KGaA who made this work possible. Especially, I want to thank to Dr. Christian Nitsch and Mr. Arnd Kessler for their support and the readiness for discussions.

I also would like to thank the team of the Section of Appliance Technology at University of Bonn. Especially I would like to thank Marina Niestrath and Stefan Dodel who conducted the washing machines tests. Furthermore I would like to thank to Dr. Gereon Broil for the technical assistance and to Maria Braun, Edith Lambert, Ina Hook and Yvonne Drechsler for their help.

I would like to thank all my friends, especially to Maria Braun, Rico Baumgartl and Jan Henning Eggert. You always believed in me and made sure that I never felt alone.

Last but not least I will forever be thankful to my family, especially my parents Mirsada and Esad as well as my brother Admir for their never-ending support in my life.

Curriculum vitae

Emir Lasic
Date of birth: December 4th, 1979
Sanski Most, Bosnia and Herzegovina

July 1998	Matura in Sarajevo, Bosnia and Herzegovina
2002 - 2005	Study of food technology science, University of Bonn
2006 - 2009	Study of nutrition and home economics science, University of Bonn
2009	Diploma Thesis: ”Akzeptanz von Haushaltsrobotern am Beispiel von Care-o-bot 3”
2009 -2014	Ph.D. student at “Household and Appliance Technology Section” of the “Institute of Agricultural Engineering” of the University of Bonn