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Construction of a Virtual Washing Machine

In the past years some researches were conducted to model laundry washing in the automatic washing machine. The most studies, however, were focused to some aspects of the automatic laundry washing (e.g. spinning cycle) and not on the washing process as whole. In this paper a model of a washing machine is presented that is based on measured data of 9 different washing machines with rated capacity between 5 kg and 11 kg, which are produced by six different manufacturers. The proposed approach is based on multiple linear regression analysis to extract the systematic, model independent behavior of washing machines and is used to calculate the consumption of the water, energy and detergent in dependence of the rated capacity, washing temperature, duration of the main wash, load size and washing performance.

Key words: Virtual washing machine, horizontal washing machine, resources consumption, washing capacity, household technology

Konstruktion einer virtuellen Waschmaschine. In den letzten Jahren begannen einige Forscher damit, den Waschvorgang in automatischen Waschmaschinen zu modellieren. Die meisten Untersuchungen befassten sich mit ausgewählten Aspekten der Maschinenwäsche (z.B. mit dem Spülvorgang) und nicht mit dem gesamten Waschprozess. Diese Untersuchung präsentiert ein Modell einer Waschmaschine, das auf den Messdaten von 9 verschiedenen Waschmaschinen mit Beladungskapazitäten von 5 kg bis 11 kg basiert. Die Maschinen stammten von sechs verschiedenen Herstellern. Der vorgestellte Ansatz basiert auf der multiplen linearen Regressionsanalyse, um das systematische, modellunabhängige Verhalten der Waschmaschinen herauszuarbeiten. Es wird eingesetzt, um den Wasser-, Energie- und Waschmittelverbrauch in Abhängigkeit von der Nennkapazität, der Waschtemperatur, der Dauer der Hauptwäsche, der Beladungsgröße und der Waschleistung zu berechnen.

Stichwörter: Virtuelle Waschmaschine, horizontale Waschmaschine, Ressourcenverbrauch, Waschkapazität, Haushaltstechnologie

1 Introduction and aim of this paper

There are different approaches to understand and to model the washing machines and the washing process. Since the beginning of the 20th century a lot of research has been done with an aim to understand the washing process [1–6].

Since 1960 the washing process is described as a function of so called washing parameters: temperature, time, chemistry and mechanics [7].

Depending on the goal of a study different approaches are used to model a washing machine and the washing process.

Ward [8] uses parametrical modelling to research the trajectory of a single concentrated mass to estimate the pressure drops that would occur on this mass as it is lifted by the baffles of the rotating washing machine drum and subsequently dropped and impacted upon landing.

Terpstra [9] conducted a 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.

In 2003, Park and Wassgren [10] conducted a computational simulation of textile dynamics inside a rotating drum. They used a simplified discrete element computational model to model the moving 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.

Rüdenauer et al. [11] conducted 2005 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 larger rated capacity to the acquisition and use of a washing machine with a rated capacity of 5 kg under environmental and economic aspects.

Lazarević and Vasić [12] used 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.

Ramasubramanian and Tiruthani [13] used computational modeling to develop firstly a simplified 2D-model and later 3D model of 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.

Mac Namara et al. [14] used Positron Emission Particle Tracking (PEPT) technique where radioactively labeled particles are monitored. In the research a single tracer particle attached to a textile is monitored as it is 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.

Stamminger [15] models the resource consumption of the complete laundry and dish cleaning process depending on various levels of efficiency of the appliances and the consumer behaviour.

The presented modelling approaches focus on specific aspect of a washing machine (e.g. exploring the influence of mechanics in a washing process), but none of the models includes the complete washing process in its model. Furthermore, those models also do not include the washing machine's rated capacity, except Rüdenauer et al.

The goal of this work is to develop a model of a washing machine ("virtual washing machine") describing the sys-

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tematic behavior of a front loading washing machine that is based on the real measured washing machines data and which enables to calculate the consumption of water, energy and detergent in dependence of the different washing machines and consumer/household related parameters. Furthermore, the virtual washing machine should offer possibility to simulate some of the variety of the different washing programs and options.

2 Material and Methods

The basis for this work is data [25] received from testing nine different washing machines with loading capacity of 5 kg, 6 kg 7 kg, 8 kg and 11 kg.

All washing machines are horizontal axis front loading washing machine with a built in heating unit. Tests were conducted in accordance to EN 60456:2011 with some modifications regarding the load (tests with 0 %, 25 %, 50 %, 75 % and 100 % of the rated washing machine load capacity) the washing program/temperature (30, 40 and 60 °C using the normal cotton program) and detergent dosage (50 %, 100 % and 150 % of the A* detergent dosage required for the specific amount of load).

Variation of all parameters (load size, washing temperature and detergent dosage) results in a total of 36 parameter combinations. Each of the combination was tested once.

The basis for the construction of the virtual washing machine model is a general equation for multiple linear regressions. The use of multiple linear regressions for modeling the washing processes has been done by other researcher such as *Terpstra* [9].

$$Y = B_0 + B_1 \times X_1 + B_2 \times X_2 + \ldots + B_n \times X_n \quad (1)$$

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

The measured data of the washing machines test is used to develop three equations where the water- and energy consumption as well as the washing performance are the dependent variables and the washing machine's rated capacity, washing temperature, duration of the main wash, load capacity and amount of detergent independent variables (Fig. 1). In order to be able to calculate the detergent consumption, the equation C is transposed. The resulting equation can be used to calculate the amount of detergent needed when a certain washing performance index is preset.

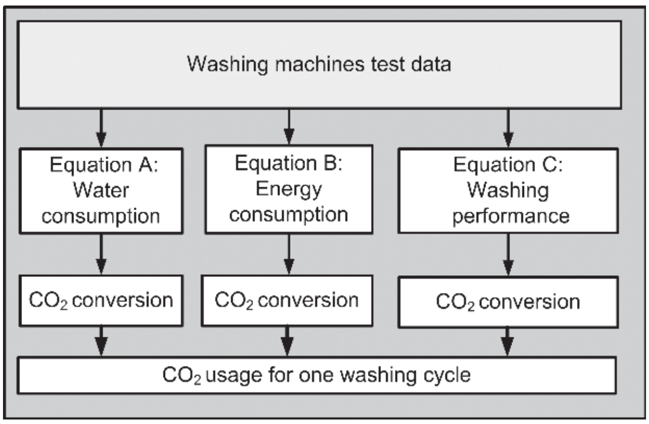

Figure 1 Schematic of the construction of the virtual washing machine (own representation)

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 Eq. (2) and the conversion factors which are valid for Germany presented in Table 1.

$$CO_2 \text{ equivalent emission} = \text{Ressource} \times \text{Conversion factor} \quad (2)$$

3 Results

3.1 Results of the washing machines tests

Water consumption increases with an increase of the load size for all washing machines tested (Fig. 2). Comparison of slopes indicates that washing machines differ in its ability to adapt its water consumption to the amount of load. 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 sensible to variation of the load. Furthermore, with an increase of the load the specific water consumption decreases. The variations in specific water consumption are lowest when washing machine is fully loaded and highest when washing machine is loaded with 25 % of the rated capacity (Fig. 3). The ratio of water consumption in the main wash to the total water consumption in dependence of the detergent dosage and in the dependence of the load size range is between 1 : 2.9 and 1 : 4.8. The mean ratio is 1 : 3.5 (Table 2, Table 3).

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. With an increase of the washing temperature in most cases the duration of the main wash increases as well (Table 4). The lowest values are reached by the washing machine WM3 at 30 °C (18 min) and the high-

Resource	Conversion factor	Gram CO_2 per unit	Unit	Source
Water	CO_2WATER	6.16	liter	[16]
Energy	CO_2ENERGY	601	kWh	[17]
Detergent	CO_2DETERGENT	1.7	gram	[18]

Table 1 Overview of CO_2 conversion factors

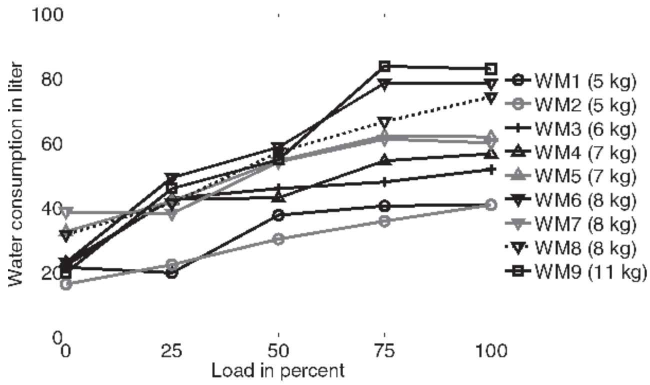

Figure 2 Water consumption of nine washing machines in dependence of the load size. Washing temperature is 60 °C and the detergent dosage is 100 % of the nominal dosage. Lines are for visualization purposes only

est values are reached by WM 9 at 60 °C (173 min). A comparison between the washing temperature set at the washing machine (nominal washing temperature) and the washing temperature measured by a sensor placed close to the heating element (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 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 5).

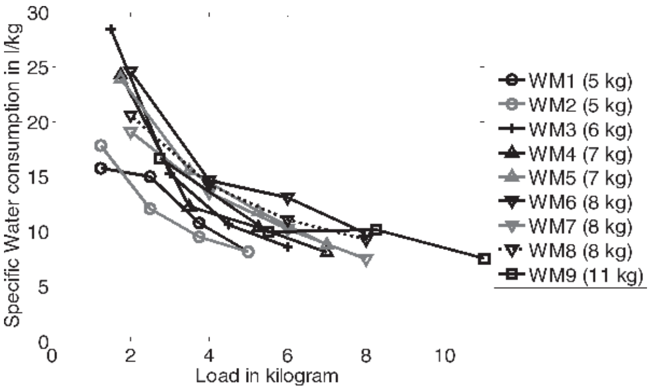

Figure 3 Specific water consumption of nine washing machines in dependence of the load size. Washing temperature is 60 °C and the detergent dosage is 100 % of the nominal dosage. Lines are for visualization purposes only

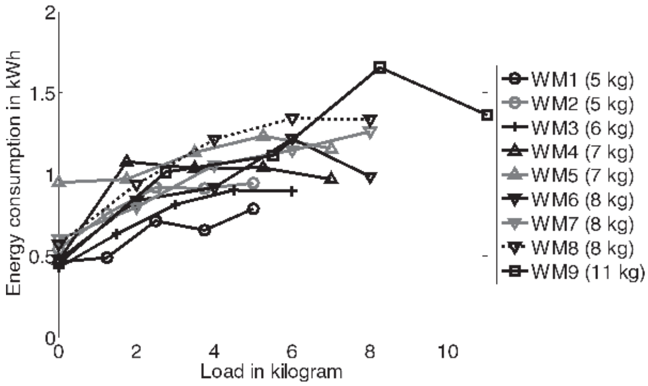

Figure 4 Energy consumption in kWh of nine washing machines in dependence of the load size. Washing temperature is 60 °C and the detergent dosage is 100 % of the nominal dosage. Lines are for visualization purposes only

	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 2 Ratio between the main wash water consumption and the total water consumption (mean values) in dependence of the detergent dosage

	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

Table 3 Ratio between the main wash water consumption and the total water consumption (mean values) in dependence of the load size

	Duration of the main wash cycle in minutes at a given nominal temperature (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

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

Average actual washing temperatures in °C			
	30	40	60
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

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

With an increase of the load size, the washing performance decreases (Fig. 5). WM3 shows the lowest washing performance index values for all loading sizes. With an increase of the washing temperature the energy consumption increases as well as the washing performance. The data shows that not in all cases the increase of the washing temperature leads to a proportionally same increase of the washing performance (Fig. 6). Comparison of the slopes shows a slightly higher loss in performance when the dosage is being reduced from 100% to 50% than from 150% to 100% (Fig. 7). Almost the same range of washing performances as achieved with different washing temperatures of 30, 40 and 60 °C can be obtained when the amount of detergent is varied between 50%, 100% and 150%. This shows that the consumer always has the possibility to select between these two parameters, wash temperature and detergent dosage, to adjust the cleaning performance he or she wants to achieve. The washing performance index values range from 0.929 in the case of the 30 °C washing cycles and 1.045 in the case of the 60 °C washing cycle (Table 6).

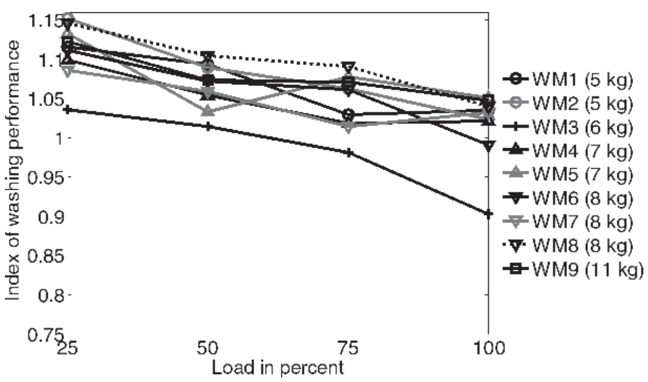

Figure 5 Index of washing performance in dependence of the load size. Washing temperature is 60 °C and the detergent dosage is 100% of the nominal dosage. Lines are for visualization purposes only

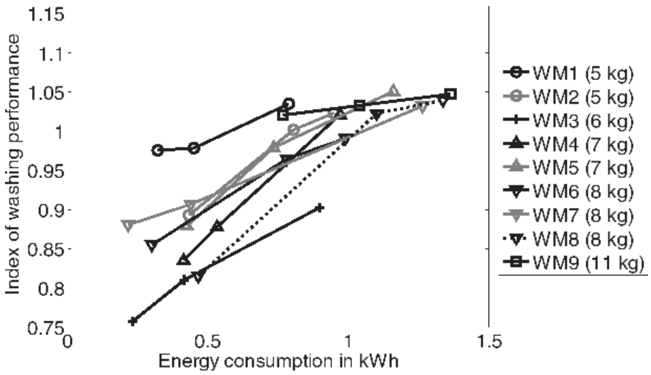

Figure 6 Index of washing performance in dependence of the washing temperatures and the respective energy consumption. From left to right the energy values indicate the washing machines' energy consumption for 30, 40 and 60 °C programs; Lines are for visualization only

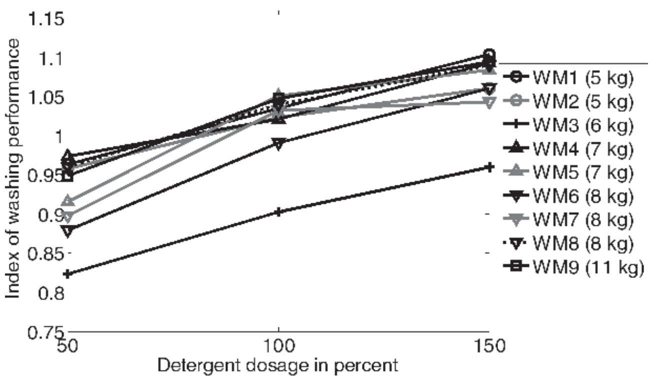

Figure 7 Index of washing performance in dependence of the detergent dosage. Washing temperature is 60 °C. Lines are for visualization only

3.2 Construction of the virtual washing machine

Basically the virtual washing machine consists of three equations each used to calculate the resource consumption (water, energy, detergent) on the basis of the virtual washing machine settings (Fig. 8).

3.2.1 Water consumption equation

The water consumption during the main wash is the most influenced by load size and the washing machine rated capacity (Table 7). A two predictor model is able to account for 88% of the variance in water consumption.

The general multiple regression equation (1) in combination with the variables selected by the multiple regression analysis (Table 7) is used to construct a model. The final

Average washing performance index at specific temperature			
	30 °C	40 °C	60 °C
WM1	0.975	0.978	1.035
WM2	0.893	1.002	1.023
WM3	0.758	0.810	0.902
WM4	0.835	0.878	1.021
WM5	0.879	0.979	1.051
WM6	0.855	0.964	0.991
WM7	0.881	0.907	1.032
WM8	0.815	1.022	1.040
WM9	1.021	1.033	1.047

Table 6 Overview of washing performance achieved at different washing temperatures (100% load, 100% detergent dosage)

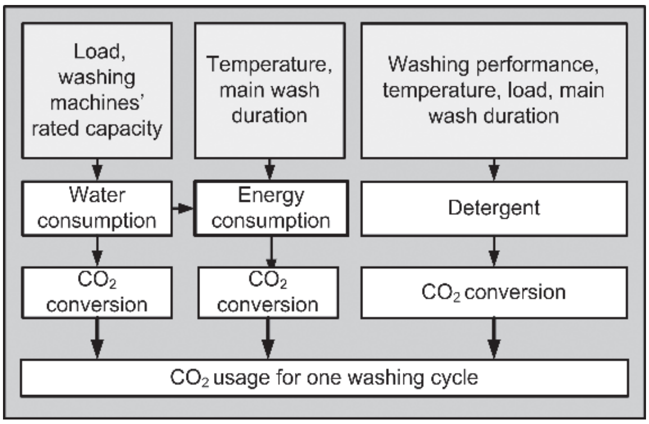

Figure 8 Schematic of a construction of a virtual washing machine and the based on the data measured during the washing machine tests

equation for predicting the water consumption during the main wash is:

$$CW_{mw} = 4.116 + 1.725 \times LOAD + 0.476 \times WMV \quad (3)$$

Where is
LOAD = amount of laundry in kg
WMV = rated capacity in kg
CW_{mw} = water consumption during the main wash in l

The average ratio between the water consumed during the main wash and the total water consumption is 1:3.5 (Table 2 and Table 3), so that the equation for calculation of the total amount of water consumed for a single washing cycle (CW_{TOTAL}) is following:

$$CW_{TOTAL} = CW_{mw} \times 3,5 \quad (4)$$

Combining the Eq. (3) and the Eq. (4) Eq. (5) results:

$$CW_{TOTAL} = 3.5 \times (4.116 + 1.725 \times LOAD + 0.476 \times WMV) \quad (5)$$

3.2.2 Energy consumption equation

The energy consumption during the main wash is mostly influenced by water consumption during the main wash, actual washing temperature and the duration of the main wash (Table 8). A three predictor model is able to account for 92% of the variance. The model was also tested by using the nominal washing temperatures. Unfortunately, the results were less accurate. The reason is explained by the large differences some washing machines show between the nominal and actual washing temperature.

The general regression equation Eq. (1) in combination with the variables selected by the multiple regression analysis (Table 8) is used to construct a model. The final equation for predicting the energy consumption during the main wash is:

$$CE_{mw} = -0.856 + 0.020 \times TEMP_{act} + 0.024 \times CW_{mw} + 0.0025 \times MWD \quad (6)$$

Where is:
CE_{mw} = amount of energy consumed during the main wash in kWh
$TEMP_{act}$ = actual washing temperature in °C
CW_{mw} = amount of water in l calculated by using Eq. (3)
MWD = main wash duration in min

3.2.3 Detergent consumption equation

The load size, detergent amount, actual washing temperature and the duration of the main wash have the most influence on the washing performance index (Table 9). A four predictor model is able to account for 82% of the variance in washing performance index.

Variable	mean	std	correlation with CW_{mw}	multiple regression weights	
				b	β
Water consumption (CW_{mw})	14.772	5.1606			
Load size (LOAD)	4.2	2.571	0.929***	1.725***	0.860
WM Rated capacity (WMV)	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

Table 7 Summary statistics, correlations and results from the regression analysis (water consumption)

Variable	mean	std	correlation with CE_{mw}	multiple regression weights	
				b	β
Energy consumption (CE_{mw})	0.525	0.3157			
Water consumption (CW_{mw})	14.74	5.021	0.470***	0.02246***	0.357
Washing temperature ($TEMP_{act}$)	41.90	11.115	0.743***	0.02040***	0.720
Duration of main wash (MWD)	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				
F = 1323.465***					

*p < 0.05, **p < 0.01, ***p < 0.001

Table 8 Summary statistics, correlations and results from the regression analysis (energy consumption)

Variable	mean	std	correlation with WP	multiple regression weights	
				b	β
Washing performance (WP)	0.992	0.095			
Load size (LOAD)	4.5	2.39	–0.255***	–0.034584***	–0.868
Detergent (DET)	93.9	48.96	0.270***	0.001194***	0.618
Actual washing temperature ($TEMP_{act}$)	42	11.16	0.467***	0.002691***	0.311
Duration of main wash (MWD)	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 9 Summary statistics, correlations and results from the regression analysis (detergent consumption)

The general regression equation (1) is used together with the variables selected by the multiple linear regression analysis (Table 9) to construct a model. The result is equation (7):

$$WP = 0.8124 + 0.0026 \times TEMPact$$
$$-0.0346 \times LOAD + 0.0012 \times DET + 0.0014 \times MWD \quad (7)$$

As the equation is intended to be used to calculate the amount of detergent consumed during a washing cycle at given washing performance index, it is transposed. The resulting equation is:

$$DET = \frac{WP - 0.8124 - 0.0026 \times TEMP_{act} + 0.0346 \times LOAD - 0.0014 \times MWD}{0.0012} \quad (8)$$

Where is:
WP = washing performance index
$TEMP_{act}$ = actual washing temperature in °C
LOAD = load of the washing machine in kg
DET = amount of detergent in gram
MWD = duration of the main wash in min

4 Discussion

4.1 Water consumption

The results of the washing machine tests and the multiple linear regression show that load size is the most influential factor on the water consumption of a washing machine. 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 [19]. Since the 1970, the water consumption of washing machines is decreasing [20] and in modern washing machines the laundry is not suspended in a bath of water, but rather only a certain amount of water is added to allow soaking of the laundry. The results of the washing machines tests indicate that all washing machines show similar tendencies regarding the water consumption. The differences among the washing machine are the highest when it is not fully loaded.

The data show that the washing machine's rated capacity influences the water consumption as well. With every increase of the rated capacity by 1 kg, the water consumption in the main wash increases by 0.476 l. All washing machines consume certain minimal amount of water in the main wash even when the washing machine is empty. This water is needed for safety reasons so that some of washing machine's components (such as the heater where the water protects it from dry heating) do not suffer damage.

During the main wash an increase of the load by 1 kg results in an increase of the water consumption by 1.725 l.

Generally, the total water consumption depends mainly on the number of rinsing cycles [21]. The number of the rinsing cycles again depends on different factors such as detergent foaming, sensitivity of the foam detection sensors etc.

As the average ratio between the total water consumption and the main wash water consumption is 1 : 3.5 (Table 2, Table 3) in the model the water consumed during the rinsing cycles is not modeled, but it is included as a constant multiplicative factor.

4.2 Energy consumption

In a washing cycle the energy is consumed for heating the water, running the main motor and the drain pump as well as for the running of the sensors, control processor and other electronic signaling units of the washing machine. The most energy, however, is consumed for electrically heating up the water in the main wash (and indirectly to some extent the laundry and the washing machine is heated up), especially when the inlet water is not preheated [21–23].

The results of the washing machines tests indicate that all washing machines show similar tendencies regarding the energy consumption.

The virtual washing model however only includes the energy consumption during the main wash. The energy consumption during the rinsing and spin phase as well as standby energy consumption is not included.

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 as good when the mentioned variances among different washing machine are taken into account.

There is a discrepancy between the nominal washing temperature and the actual washing temperature (Table 5) and for this reason in the energy equations the maximally reached actual washing temperature is included. With beta values of 0.72 (Table 8) 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.

The energy consumption also depends on what the manufacturer want to offer to the consumer as a standard washing program. In some cases the manufacturer offer a shorter program as standard and the consumer have to use the "intense" or "stains" option to extend the program. Other manufacturer offer a longer washing program as a standard program and the consumer have to choose "express" or "short" option in order to shorten the washing program [24].

4.3 Detergent consumption

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 (3) what kind of detergent to use and how much to dose. In the equation some of those consumer patterns are included, and each of those can be adjusted separately.

The beta values of the multiple regression analysis show that actually the load size has the highest impact on the washing performance index of all variables. With every ceteris paribus increase of the load size the washing performance index decreases (b value of –0.0346). In accordance with [7], with a lower load size the free space in the drum increases and hence the laundry has more space to tumble down and so the mechanical force is increased. When all other factors are kept constant, an increase of the washing performance index occurs by reducing the relative load size.

With every increase of the washing temperature by 1 °C results in an average increase of the washing performance index by 0.0026. Similar is the case with the influence of the amount of detergent and the duration of the main wash. Every increase of the detergent by 1 g and every increase of the duration of the main wash by 1 min results in an average increase of the washing performance index by 0.0012 (DET) resp. 0.0014 (MWD).

As the Eq. (6) shows the results of the multiple regressions analysis set the washing performance as dependent variable and the washing temperature, load size, amount of detergent and duration of the main wash. With the Eq. (8) it is possible to preset the washing temperature, duration of the main wash, load size and washing performance and so calculate the amount of detergent needed.

In the virtual washing machine model it is possible to combine the variable "duration of the main wash" and variable "washing temperature" in order to simulate a washing program. So for example an intensive washing program can be simulated by increasing the "duration of the main wash" variable and increasing the "washing temperature" variable. A more ecofriendly washing program can be simulated by increasing the "duration of the main wash" and lowering the "temperature" variables.

In the equation the actual washing temperature is included. The reason for this is that there is a discrepancy between the nominal and actual washing temperature. Not all washing machines have reached the washing temperature which was preset (Table 5).

5 Conclusion

Data of nine washing machine test showed that, despite some exceptions, all washing machines display similar tendencies and that a mathematical model of a washing machine is generally possible. In the case of each of three equations, a large portion of the variance in the data can be explained by the included independent variables.

In order to develop a virtual washing machine three different equations, each used to predict the consumption of one of the resources, are developed.

Although the washing machines differ regarding the rated capacity, implemented engineering solutions and sensors as well as designed washing/programs, it is possible to develop a virtual washing machine that predicts the resource consumption well, and which is in line with the data measured on the washing machines on the German market (e.g. data from [26]).

The virtual washing machine offers the possibility to vary many variables. Such a model can be used to simulate the laundry washing behavior of the consumer to some extent. So, for example, it can be used to simulate the previously described consumers' possibility to vary wash temperature and detergent dosage and so adjust the cleaning performance he or she wants to achieve. Such a simulation could be used to identify the pros and cons for the consumer of those scenarios.

The virtual washing machine has also some restrictions. It does not consider the new features implemented in state of the art washing machines such as automatic dosing since none of the nine tested washing machines had such a feature. Its influence on the model should be further examined. Furthermore, a follow up model should also incorporate data of washing machine tests with liquid detergents and other types of load than cotton.

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