Application

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Brevity is the soul of wit – how time, temperature and detergent choice impact the cleaning performance in domestic dishwashers

Abstract: In addition to high cleaning performance, many consumers pay special attention to low energy and water consumption in automatic dishwashers. Eco programs are designed to effectively clean normally soiled dishes with low energy and water consumption. However, Eco programs are relatively long and consumer acceptance of programs lasting longer than 2 h is not very high. The vast majority of short programs for lightly soiled dishes consume equal to lower amounts of energy and water than Eco cycles on average. In this study, we investigate the effect of different dishwasher programs on the cleaning performance for a variety of soils using four different market detergents. The results show that the detergent has a major influence on the cleaning result, especially for short cycles and that for certain short cycle/cleaner combinations similar good results can be achieved as with Eco cycles. The data collected were also used to train predictive models to make forecasts on cleaning performance for unknown program parameter combinations, and to examine the multivariate relationships of the program parameters and the cleaners in more detail.

Keywords: dishwasher; short cycle; cleaning performance; household; detergent

1 Introduction

Population growth and improvements in living standards, especially in industrialized nations, have led to an increase in the use of household electrical appliances for many decades [1]. With the increasing concern for environmental sustainability, there has also been a focus on energy and water consumption of household appliances, such as dishwashers [2]. As dishwashing is a daily household task [3] dishwashers play an important role in modern households. In addition to a high cleaning performance, low energy and water consumption are important to consumers [4]. In this regard, the Eco-cycle was defined as a test program for declaration purposes and should therefore have the lowest possible energy and water consumption when cleaning normally soiled dishes [5]. The low consumption is mainly achieved by the longer program duration at lower temperatures (about 50 °C). Although programs lasting up to over 4 h would be not regularly used by many consumers [5–7] and 31 % of the consumers in 6 EU countries found it too long [7]. A survey conducted in 11 countries showed that approx. 65 % of consumers do not generally accept longer programs in order to save energy [5]. In addition, many consumers do not recognize the connection between longer cycle times and lower energy consumption, or even assume that shorter cycles generally consume less energy [8]. About 18.5 % of the respondents of a survey in 10 European countries consider short cycle lengths as important [9]. Especially short programs that are shorter than 1 h may even show lower energy (Table 1) and water consumptions than Eco-cycles but according to the manufacturer, these short cycles of less than 55 min and about 30 min cycle length on average (Supplementary material, Table S1) are intended for rather lightly soiled dishes [10]. Programs of about 1 h cycle length often have higher temperatures in the main wash and drying phase and therefore consume more energy [10]. Alt et al. recently evaluated the impact of three recommendations on program selection and their effect on overall energy consumption [10]. The findings revealed that implementing these recommendations could lead to an energy saving of more than 20 % and water savings of 18 % without...
compromising on cleaning performance [10]. The used approach incorporated data on average energy and water consumption, program duration, and the probability of program usage in different countries. By combining these factors, the average energy and water consumption were calculated. The first recommendation based on the study’s results advises against using program modifiers like “express/speed/quick/time-saving” due to its substantial additional resource requirements, including energy and water [10]. The second recommendation encourages using the Eco-program for normal dish loads, despite the longer duration, as it effectively cleans dishes while minimizing resource usage. For lightly soiled dishes, the third recommendation suggests utilizing the short cycles (quick/fast, 45 °C, Jet, 30’, express) programs [10]. However, the study does not provide information as to whether economical short programs could possibly achieve the same cleaning performance as the Eco program through optimized cleaning agents. Since at least 18.5% of the consumers want shorter cycles [9] and a majority cares about energy and water consumption [4], short cycles are of great importance. In our previous study, we showed that short programs, which last only about 30 min on average and use little energy and water, could be an economical and convenient alternative to the more time-consuming Eco programs [11]. Some of the short programs investigated in this study show less energy consumption (0.74 kWh on average) than the standard Eco programs (0.90 kWh on average) for a full dishwasher load [11]. However, if the cleaning performance is ultimately poor, these programs might not play a role in the consumers’ choice. Therefore, we investigated how different parameters, namely temperature, time and water volume, affect cleaning performance when using different market cleaners. We focused on capsules and tablets, since a large majority (76% in a survey of 2599 people) use detergent in predosed form, such as tablets for automatic dish washing [12]. With the experimental data obtained, mathematical prediction models were trained to make predictions about the cleaning performance for any combination of parameters, taking into account individual tested soils. These first models might be used to make suggestions for very specific cycles and create a deeper understanding of the interrelationship of individual parameters, as well as to evaluate the effect of different cleaners on the cleaning performance of particularly short and low-consumption cycles.

2 Materials and methods

<table>
<thead>
<tr>
<th>Number</th>
<th>Energy consumption (kWh)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short</td>
<td>1 h</td>
<td>Eco</td>
</tr>
<tr>
<td>1</td>
<td>0.800</td>
<td>1.180</td>
<td>0.930</td>
</tr>
<tr>
<td>2</td>
<td>0.783</td>
<td>1.236</td>
<td>0.735</td>
</tr>
<tr>
<td>3</td>
<td>0.54–0.66</td>
<td>0.8–0.93</td>
<td>0.821</td>
</tr>
<tr>
<td>4</td>
<td>0.50</td>
<td>0.968</td>
<td>0.590</td>
</tr>
</tbody>
</table>

Table 1: Information about tested cycles and energy consumption.

The individual short cycle, 1 h cycle and Eco cycle of four standard household dishwashers (85 cm height, 60 cm depth, 60 cm width) were used (Table 1). The values for energy consumption were determined by using what was declared by each manufacturer in the dishwasher manuals. For dishwasher number 2, energy consumption was measured using an energy meter plug (Maxcio ASIN B07Y13RK2B), as no information was available in the manual.

Figure 1 shows the different temperature profiles of the four different dishwasher models used. The initial water inlet phase was omitted here. Two Eco cycles (machine 3 and 4) have a cold initial rinsing phase.

The final drying phase (section of the curve after rinse 2 (Figure 2)) was not taken into account, since it has no effect on the cleaning performance nor on water or energy consumption. The subdivision of the cycle, as used for the later predictive model development, is shown in Figure 2.

2.2 Cleaners (automatic dishwashing detergents)

All cleaners are branded products from three different leading manufacturers. All products are multifunctional products (pouches or tabs). The cleaners are referred to below as A–D (Table 2). The 4 products tested are representative of the European market and of different product segments ranging from higher to lower technical performance.

2.3 Preparation of teacups and crème brûlée plates

Both the teacups and the crème brûlée plates were prepared according to the IKW protocol chapter 2 and chapter 9 [13].
2.4 Preparation of ballast soil

Five grams ballast soil units were produced according to Table 4 production instructions for ballast soil from the IKW Recommendations for the Quality Assessment of the Cleaning Performance of Dishwasher Detergents [13].

2.5 Execution of the dishwasher test runs

A total of four dishwasher models with four cleaners, three cleaning programs and four repeat measurements were tested. The four different dishwasher models were all operated in parallel using hardened water according IKW protocol [13]. The dirty items were placed in the upper rack of the dishwashers in the order shown in Table 3. Two of each soiled item types were used, which means that after the sequence as shown in Table 3, this sequence was repeated again and thus 10 CFT-tiles were lined up in a row.

Five plates with baked crème brûlée were added in the bottom dishwasher rack and two teacups in the top rack; one in the corner at the back and one in the corner of the front. The frozen ballast soil was placed underneath a mug which was placed in the upper rack. The above described placement of the individual items is shown schematically in Figure 3. Areas marked “clean” are CFT-tiles or plates without soiling, which serve as splash protection.

The cleaner was placed in the dispenser. After the machines were fully loaded, the test programs were started and run to completion. A temperature logger Thermo Button (VWR International, Pennsylvania, USA) was placed in the upper drawer in each run to subsequently monitor compliance with the expected temperature profiles.

2.6 Cleaning performance evaluation

The items to be analyzed were labeled after cleaning to ensure accurate allocation. The teacups were rated by two independent panelists according to the 0 to 10 scale according to Figures 3 and 8 of the IKW

Table 2: Tested products with short description.

<table>
<thead>
<tr>
<th>Product A</th>
<th>Product B</th>
<th>Product C</th>
<th>Product D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Branded multifunction capsule powder/liquid–high tier</td>
<td>Branded multifunction capsule powder/liquid–high tier</td>
<td>Branded all in one hard pressed tablet–low tier</td>
</tr>
<tr>
<td>Ingredient labeling</td>
<td>5–15 % non-ionic surfactants, oxygen-based bleaching agents, &lt;5 % (phosphonates, polycarboxylates), enzymes, perfumes</td>
<td>15–30 % non-ionic, 5–15 % oxygen based bleaching agents, polycarboxylates, phosphonates. Contains enzymes (subtilisin, amylase), perfumes</td>
<td>5–15 % oxygen based bleaching agents, phosphonates, &lt;5 % polycarboxylates, non-ionic surfactants, enzymes (subtilisin, amylase), perfumes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Branded multi active hard pressed tablet–high tier</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5–15 % bleaching agent of oxygen base, phosphonate, polycarboxylate, non-ionic surfactant (&lt;5 %), other ingredients (fragrance, enzyme)</td>
</tr>
</tbody>
</table>
protocol [13] and all soiled items were measured before and after test runs using an image analyzer, resulting into % stain removal index (SRI).

2.7 Calculation of multivariate predictive models

In order to make predictions for new unknown cycles with the existing data and to investigate the influence of different parameters on the cleaning performance in more detail, predictive models were trained via MATLAB R2022b (MathWorks, Natick, MA, USA) Regression Learner Toolbox using support vector machines (SVM) with the following hyperparameters: kernel function: cubic, kernel scale: automatic, box constraint: automatic, epsilon: auto, standardize data: yes. Besides the dishwashing detergents (cleaners A–D) themselves as categorical variables we have chosen the device parameters with the corresponding values (Table 4), as input parameters for training the models. We split the cycle time in the times of possible initial rinses before main washing takes place (rinse 0), the main wash times themselves, time of rinses that take place after main wash, but which are not the main rinse (rinse 1) and the main rinse time taking place with the maximum rinsing temperature (rinse 2). Since not every rinse phase is present in every cycle, we have only added the temperatures of the main wash and main rinse as parameters.

2.8 Predictions for unknown cycles

A permutation matrix was first created, considering all values found in Table 5. Selected values were within the range of the short cycles (Supplementary data S1). In principle, 4,939,200 combinations were possible, based on the product of all available values (Table 5). However, impossible combinations were eliminated, resulting in a total of 3,358,656 combinations. Otherwise, all combinations and also extremes were included, even if unlikely or difficult to implement in practice in order to obtain the broadest possible first impression (for example, reaching a cleaning temperature of 65 °C with only 10 min of washing time and a large amount of water is highly unlikely). Predictions were made for these combinations using the SVM models and various parameters were plotted to identify patterns and draw possible multivariate conclusions.

3 Results

3.1 Cleaning performance

As shown in Figure 4, the cleaning performance of the Eco cycles was consistently high, achieving reductions of around 65 %–93 % for almost all soils. However, cleaner C performed poorly with machine 4 in the Eco programs for protein-based soils like BEY (SRI of 27 %), BC and DM (SRI of 42 %). For the starch-based soils (MS & RS), cleaner C and Eco performed better (SRIs of 74 % and 72 %). Thus, with the exception of cleaner C, the individual cleaners have little effect on cleaning CFT-tiles (Figure 4) and crème brûlée soils (Figure 5) when using the Eco programs. Cleaner D also showed a lower performance with the Eco program parameters of machine 4, whereas cleaners A and B achieved high SRI of about 65 %–88 %. In the Eco cycles, cleaner A with machine 3 parameters achieved the highest cleaning performance. The 1 h programs showed higher reductions for cleaner C and machine 4 than the corresponding Eco cycles. Likewise, the individual cleaners had a more visible influence on the cleaning result of the 1 h cycle compared to the Eco cycles (Figure 4). Especially with protein-based soiling (BEY, BC, DM), cleaner C shows very low performance in the 1 h cycles. This trend continued for shorter durations, which means that the SRIs for the short cycles using cleaner C were even lower than with the 1 h cycles.

Except for starch containing soils (MS, RS), the low performance of cleaner C was evident in the short cycles

![Table 3: Used test soils (CFT-tiles) and their subsequently used abbreviation.](sample_table)

<table>
<thead>
<tr>
<th>Position</th>
<th>Designation</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Boiled egg yolk</td>
<td>BEY</td>
</tr>
<tr>
<td>2</td>
<td>Cheese, baked</td>
<td>BC</td>
</tr>
<tr>
<td>3</td>
<td>Minced meat, double soil load</td>
<td>DM</td>
</tr>
<tr>
<td>4</td>
<td>Mixed (corn/rice) starch, colored</td>
<td>MS</td>
</tr>
<tr>
<td>5</td>
<td>Rice starch, colored</td>
<td>RS</td>
</tr>
</tbody>
</table>

![Figure 3: Exemplary loading plan of the test series.](sample_figure)
investigated. The short cycle of machine 2, which was comparatively longer than the other short cycles (Figure 1) and consumed more energy (Table 1), achieves the highest SRI on average (short cycles). Cleaners A and B achieved very high SRIs even in the short cycles. For example, the SRI for BEY ranged from 57 % to 73 % for cleaner A and from 56 % to 74 % for cleaner B. For BEY, the major influence of the cleaner is also evident under otherwise constant short parameter conditions (machine 1), where cleaner A achieved 57 % SRI and cleaner B 68.1 %. This trend was also evident for the other two protein-based CFT-tile soils (BC, DM), with cleaner A achieving lower SRI overall than cleaner B for DM. However, the reverse was true for the starch-based CFT-tiles, where cleaner A performed considerably better for MS (mean SRI 70 %) than cleaner B (mean SRI 48 %), and better for RS (81 % SRI for cleaner A and 74 % SRI for cleaner B).

Considering the averaged values of all CFT-tiles (Figure 6), it becomes apparent that cleaner A and B using the short program parameters of machine 2 and 3 showed only slightly worse SRI results than the corresponding Eco and 1 h programs. These combinations (cleaner A or B with machine 2 or 3 short cycle parameters) could achieve higher cleaning performances than certain 1 h and Eco programs using cleaner C or D. Overall, however, the cleaning performance of almost all short cycle combinations is lower than that of the Eco cycles.

The baked crème brûlée plates were completely cleaned with all Eco cycles (Figure 5). In the 1 h cycles, cleaner A and B showed high reductions with almost complete soil removal with the program parameters of machines 2 and 3 and 7.7–8.9 (10-point scale) with machine 1 and 4.

In the short cycles, cleaner A with machine 2 parameters showed the highest crème brûlée reduction (8.0). In contrast, almost no removal of the crème brûlée soil was possible with the short cycles (1.0–3.1) with cleaner C.
Cleaner A showed a high performance in the short cycles and was only just below the 1 h and Eco programs for tea. With certain restrictions (machine 2 and 3), cleaner D could also effectively clean the tea soil in the short cycles. Cleaner B, which showed high performance on the protein-based soils, showed some weakness on tea. There, almost no cleaning was seen in combination with machine 3 and 4 short parameters. The 1 h and Eco cycles showed almost complete removal on tea when using cleaner A and D, whereas cleaner B and C performed weaker.

**Figure 4:** SRI in % for individual CFT-tiles using all cleaners (A–D) and machines [1–4].
### 3.2 Model development

Individual SVM based prediction models were trained for each soil using 5-fold cross-validation. For the CFT-tiles an additional model was trained containing the SRI-mean values of all CFT-tiles (BEY, BC, DM, MS, RS) as the response values. Figure 7 shows an example of the cross-validated predictions plotted against the actual values of the model for all averaged CFT-tiles (a), crème brûlée (b) and tea (c). $R^2$ of the cross validation for the model of all CFT-tiles was 0.922 and the root mean square error (RMSE) was 4.38. The $R^2$ value of the model predicting the cleaning performance for crème brûlée was in a similar range at 0.918 with an RMSE of 0.83. The predictions for the teacups are most scattered and the model showed an $R^2$ of 0.874 with an RMSE of 1.08. The model performances of the individual CFT-tile soils were in a similar range as the model for the SRI mean of all CFT-tiles with $R^2$ ranging from 0.820 to 0.924 (Table 6). The largest RMSE for the CFT-tile models was 6.97 for BC. The individual model performance parameters ($R^2$ and RMSE) can be obtained from Table 6.

Figure 8 shows the result of an $F$-test performed within the MATLAB Regression Learner app. The Importance Score reflects the importance of a predictor to accurately predict the SRI for the averaged CFT-tiles soiling by the SVM. This does not automatically mean that parameters with high importance scores have the greatest influence on high cleaning performances. The highest influence to make accurate predictions was the duration and then temperature of rinse 2, closely followed by the duration of the main wash. The influence of the predictors of water consumption for rinse 1, the main wash and rinse 2 were almost identical. The temperature of the main wash, with an importance score of 40.9, is still important for accurately predicting the SRI.
The duration and the amount of water of rinse 0 had only a very small influence on the predictive model. The cleaners showed a much higher importance score than time and water consumption of rinse 0, but it was far below the remaining predictors.

### 3.3 Predictions for unknown cycles

Predictions were made for the combinations in Table 5 using the SVM model for the cleaning performance of the averaged CFT-tiles. The predictions were subsequently placed in a matrix next to the corresponding predictors and then all rows were sorted in descending order of SRI size. Subsequently, various parameters were plotted to identify patterns and make possible multivariate conclusions.

Figure 9 shows the chronological scheme of the results’ interpretation using the example of cleaner A. The predictions of the corresponding SVM models for soil removal, for example the mean of all CFT-tiles in SRI, can be plotted as a 3-dimensional surface (Figure 9a) to subsequently isolate, for example, individual cycle combinations based on their main cleaning temperature or cleaning performance. Figure 9b is a lateral plot of Figure 9a to evaluate overall trends and allow general conclusions. Predictions were also sorted by size of the SRIs and then plotted (Figure 9c) to better identify trends. Figure 9d shows the gradients of sorted cleaning performance from the surface of (c). In the following, the 3-dimensional representation of the predictions unsorted (a) and sorted (b) are omitted and the lateral representation of the prediction profiles (b) and (d) is used.

**Table 6:** Individual SVM model performance parameter $R^2$ and RMSE using 5-fold cross-validation. For RMSE, the unit to note is percent (CFT-tiles), and for CB and tea, a scale from 0 to 10.

<table>
<thead>
<tr>
<th>Soiling</th>
<th>$R^2$</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean all CFT-tiles</td>
<td>0.922</td>
<td>4.38</td>
</tr>
<tr>
<td>BEY</td>
<td>0.884</td>
<td>6.77</td>
</tr>
<tr>
<td>BC</td>
<td>0.886</td>
<td>6.99</td>
</tr>
<tr>
<td>DM</td>
<td>0.924</td>
<td>5.01</td>
</tr>
<tr>
<td>MS</td>
<td>0.890</td>
<td>6.15</td>
</tr>
<tr>
<td>RS</td>
<td>0.820</td>
<td>4.98</td>
</tr>
<tr>
<td>Crème brûlée (CB)</td>
<td>0.918</td>
<td>0.83</td>
</tr>
<tr>
<td>Teacups (tea)</td>
<td>0.874</td>
<td>1.08</td>
</tr>
</tbody>
</table>
Figure 10 shows the predictions made for all cleaners in all combination possibilities from Table 5 for the SRI of all averaged CFT-tiles under visual consideration of the main wash temperature. The first thing to notice is that there are a few combinations that result in cleaning performances (SRI values) above 100 %. A plausibility check could restrict predictions to a maximum of 100 % SRI. In this study, this was deliberately not done in order to show possible limitations of the models.

Considering the SRI of all averaged CFT-tiles, cleaners A and B performed very similarly, but the variation was larger for cleaner A. The smallest value, i.e., the least effective possible cycle combination in terms of cleaning performance, was also lower with cleaner A (approx. 20 % SRI) than with cleaner B (approx. 35 % SRI). Cleaners C and D were predicted significantly worse with a predicted maximum possible SRI of approx. 84 %. At a main wash temperature of 45 °C, a maximum of approx. 56 % SRI was possible for cleaner C, and approx. 66 % for cleaner D. The predictions also showed that cleaner C and D were less suitable for short cycles and normally soiled dishes (according to the combinations of Table 5) if a high cleaning...
performance was to be achieved. In the predictions considering each cleaner, it was noticeable that at the lowest temperature (below 40 °C) the SRI can again become higher. The lowest temperature available in the data set for the predictive model development is 40.6 °C and is thus above the range for which predictions were made which indicates an extrapolation takes place when forecasting.

The patterns in Figure 10 also allow for cleaner-specific statements. For example, with a 65 °C main wash, taking into account the other parameters in Table 5, the cleaning efficiency (SRI) for the average of all CFT-tiles could not be less than about 62 % when cleaner B was used, 56 % when cleaner A was used, 42 % using cleaner C, and 44 % with cleaner D. On average, at 50 °C main wash temperature, both cleaner A and cleaner B achieved SRIs of about 67 %, whereas for cleaner C SRI was about 42 % and for cleaner D approx. 47 %.

As can be seen from the process sequence in Figure 9, the SRI were sorted in ascending order and then individual curves were plotted which could be found for all cleaners and the main wash temperature parameter in Figure 11. Based on these curves, a particularly convenient interpretation of the cleaning performances achieved at the corresponding main wash temperature is possible. If one is looking for a cycle which has a good cleaning performance, but still allows a good differentiation of an investigated cleaner, it makes sense to look at values exactly in the middle of certain curves shown in Figure 11. Here, the comparison of two closely neighbored points in these curves allow for interesting statements to be made with regard to parameter variation with almost identical cleaning performances.

For example, looking at the curve of cleaner A in Figure 11 and selecting the two data points in the middle of the curve at positions 59,976 and 59,977, one can isolate the values depicted in Table 7.

This allows for statements like that for cleaner A, using 50 °C in the main wash cycle, 22 min can be saved if rinse 2 lasts 8 min longer and 5 l instead of 4 l water are used in the main wash cycle. On the other hand, 5 l of water could be saved overall by using the longer main wash cycle.

Figure 10: Plot of SRI values predicted via SVM for all averaged CFT-tiles in the selected predictor range of cleaner A–D with visual consideration of the different main wash temperatures.
4 Discussion

4.1 Cleaning performance

Short programs consume similar to less energy (Table 1) and water (Table 4) versus Eco cycles, but in a much shorter time period. However, according to the manuals of the machine manufacturers, the short programs should mainly be used for lightly soiled or prerinsed dishes. Consequently, Alt et al. [10] recommended recently to choose the short program as an energy saving measure if only lightly soiled dishes have to be cleaned [10]. However, our experiments show that in short programs cleaners may compensate for the lower temperatures, water amounts and mechanical actions as well as time in Sinner’s sense [14] by optimized chemistry. Although, since market products have been used, no details of the contents of the cleaners (A–D) could be disclosed in this study, some important conclusions can be drawn. Our results show that there are products available on the market that can achieve high cleaning performance for normally

Table 7: Parameter combinations in the SRI prediction of the two values exactly in the middle of the 50 °C curve of cleaner A (Figure 11). In order to achieve an almost identical cleaning performance at identical temperature, these different parameter combinations could be used.

<table>
<thead>
<tr>
<th>SRI</th>
<th>Time (min)</th>
<th>Water consumption (L)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main wash</td>
<td>Rinse 0</td>
<td>Rinse 1</td>
</tr>
<tr>
<td>67.4</td>
<td>14</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>67.4</td>
<td>22</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 11: Ascending sorted predicted SRI values via SVM model for the mean CFT-tiles showing each main wash temperature. The curves represent the SRI obtained over all predicted predictor combinations considering individual temperatures in the main wash.
soiled items even with short cycles, which according to the manufacturers were intended mainly for lighter soiling. Considering the energy consumptions listed in Table 1 and the average cleaning performance for all CFT-tiles, energy savings would be possible, especially with the combinations of cleaner A or B with the short cycle program parameters of machine 2 or 3. It must be noted that the short cycle of machine 2 takes a relatively long time and, at 0.783 kWh is not more economical than the Eco program parameters’ combination of the same machine, although this is the machine that delivers the highest absolute cleaning performance. The short cycle parameters’ combination of machine 3, on the other hand, saves approximately 0.221 kWh compared to the corresponding Eco program, which is equivalent to 80.67 kWh per year if the dishwasher is used daily. With a cycle length of only 34 min instead of 2 h and 41 min (without drying phases), consumers who prefer shorter cycles but want to save energy and water might use this kind of short cycle even with normally soiled dishes by choosing the appropriate cleaner. The drying performance was not examined in our study, but is important. If short cycles with high cleaning performance and low energy and water consumptions were to lead to wet dishes, consumers would be dissatisfied with the overall result. With 64.6 % and 58.1 % SRI on average over all CFT-tiles (Figure 6) using cleaner A or B, the short cycle parameter combination of machine 4 provides a relatively high cleaning performance with an energy consumption of only 0.5 kWh. Main reason for the low energy consumption of the short cycle of machine 4 is that there is no additional hot rinsing phase after the main wash. However, since not all given short cycles and cleaners’ combinations lead to cleaning results comparable to Eco or 1 h programs, consumers would have to test this out first. In their 2016 study, Gorny et al. [15] conclude that the effect of the cleaning temperature factor exceeds the effect of the time factor. The biggest influence on the energy consumption of the dishwasher is the temperature. The decrease in cleaning performance of a dishwasher at lower cleaning temperatures, can partly be compensated for by adjusting the detergent formulation accordingly [16].

4.2 Predictive models

Our predictive models provide estimates for cleaning individual soils of arbitrary program combinations, considering the four cleaners included in the data as well as the other predictors. The five-fold cross-validated models show high $R^2$ and for the most part very small RMSE, indicating robust model performance. However, the predictive models should also be validated in practice and extended (further research) for example, to identify ideal short cycles for a given task. In the predictions (Figure 10) for the permuted cycle combinations from Table 5, it is noticeable that at the lowest main wash temperature (35 °C) the SRI can increase. The minimum temperature within the training data set was 40.6 °C and is thus above the range for which predictions were made which means that an extrapolation takes place. Presumably, the models “learned” that at very low main wash temperatures, the cleaning performances were not too low, because the data contained in the data set, i.e., the cleaning programs, then often lasted much longer or had a more vigorous rinse cycle. Therefore, it must be considered that the accuracy of the predictions may decrease for areas outside the reference values included in the model. Nevertheless, the lowest main wash temperature also yielded the lowest SRIs, which can be considered very likely in practice and testifies to the performance of the predictive models. Of course, the data collected and the models trained allow a much deeper insight as each parameter (predictor) can be considered separately, as well as the individual soils. In this study, the main objective was to train models in general, to assess their eventual performance and to estimate their potential. The exemplary $F$-test for the model predicting SRI of all averaged CFT-tiles was examined to assess the overall significance of the individual predictors. The cleaner shows a significantly higher importance score than rinse 0, but it is still far below the other predictors (Figure 8), which indicates that the cleaner does not have a strong influence on the overall data contained in the training set. However, it is evident from the experimental data (Figures 4 and 5) that the influence of the cleaner is very strong, especially for the short cycles, whereas the cleaner has only a weak effect on the most Eco cycles. Since the temperature of the main wash cycle should have a major influence on the cleaning result [15], it is particularly interesting that this predictor seems to be relatively unimportant for accurately predicting the SRI. This may confirm the difficulties of interpreting complex predictive models like SVMs. However, the main wash importance score differs from the four next higher rated predictors by only about 12 %-17 %.

5 Conclusions

Consumer acceptance of long-lasting cycles and their regular use has been shown to be limited [5–7]. However, in addition to clean dishes, consumers are also interested in low energy and water consumption [4]. Thus, short cycles that also deliver a high cleaning performance could be of great interest to many consumers. We could show that this is possible with
some combinations of performing cleaners and dishwashers’ programs available on the market. We performed a cycle performance mapping across 4 different machine models and 3 different cycles (short, 1 h and Eco) with 4 different market products. Our results confirm that, due to the overall lower temperatures and shorter time, short cycles require more powerful or especially designed products to achieve higher cleaning levels. Short cycles in combination with high performing cleaning products are suitable to tackle more than lightly soiled dishes and might be suitable for everyday cleaning. Not only the dishwashing product, but especially the cleaning products are suitable to tackle more than lightly soiled dishes. Short cycles in combination with high power or especially designed products to achieve higher cleaning levels. Short cycles in combination with high power or especially designed products to achieve higher cleaning levels.

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References

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