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Published in:
Proceedings of the 2020 IEEE/SICE International Symposium on System Integration, SII 2020

DOI:
10.1109/SII46433.2020.9026279

Publication date:
2020

Document version:
Accepted manuscript

Citation for pulished version (APA):
Værbak, M., Ma, Z., Christensen, K., Demazeau, Y., & Jørgensen, B. N. (2020). Agent-Based Simulation of Implicit Demand Response Adoption for Water Distribution System Reservoirs. In *Proceedings of the 2020 IEEE/SICE International Symposium on System Integration, SII 2020* (pp. 891-896). [9026279] IEEE. https://doi.org/10.1109/SII46433.2020.9026279

Agent-Based Simulation of Implicit Demand Response Adoption for Water Distribution System Reservoirs

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Abstract— **The electricity production from intermittent renewable energy sources, such as wind and solar power, has increased significantly, which requires the electricity grid to be gradually restructured through different approaches. Demand Response (DR) is one of the examples which is applicable to a broad variety of electricity consumers, from households to sizable industrial processes. However, there is a barrier to implement DR in that consumers may not be willing to change their behaviour or invest in energy management technologies without gaining enough monetary benefits from doing so. The purpose of this study is to investigate the behaviour of electricity consumers who are offered implicit DR solutions and to investigate which parameters that characterise the consumers who adopt these solutions. The study applies an agent-based simulation model that uses separate and independent modules for the domain logic, the business solution logic and the DR adoption decision logic, respectively. Furthermore, the case study chosen for the simulation is a population of domestic water distribution system water towers with pumps whose operation can be coordinated with the hourly electricity prices from the day-ahead spot market. The simulation results show that tower/pump pairs on water distribution systems with higher water demands adopt the implicit DR solution faster. The pumping rate and tank capacities do not have significant impact on the adoption, at least not if they are beyond a certain size. Meanwhile, the simulation also finds the maximum investment cost for the implicit DR solution to be 71,000 DKK, if half of a water tower population must adopt the solution within a 5-year ROI period.**

I. INTRODUCTION

With the increasing urgency to divert the energy sector towards carbon neutrality, significant changes need to be made to the structure of the various energy systems within the upcoming years. Many of these changes require that actors who interact with the energy systems adopt new technologies, solutions or behavioural changes (called *solutions* in this paper). It is not only important how large a share of a consumer segment, e.g., residential electricity consumers, that adopt a specific solution but also how fast it happens. Due to the time-dependent nature of climate changes and thus climate goals and policies, the adoption rate of a solution by a specific group of energy consumers is crucial if the Paris Agreement goal to prevent a global average 2 °C temperature increase from pre-industrial level [1] should be fulfilled, and that the Danish energy sector should reach climate neutrality by 2050 [2].

One popularly discussed solution that might be crucial in the transition towards a carbon-neutral energy sector is Demand Response (DR) where electricity consumers are encouraged to change their electricity consumption behaviours and patterns in accordance with supply on the electricity market and efficient operation of the power grid. The behaviour changes can either be maintained by the consumers themselves or other parties, and they can be based on a simple response to a price signal (implicit DR) or a market where consumption flexibility is traded as a commodity (explicit DR) [3, 4]. This approach fits especially well with the increasing amount of intermittently produced energy in the grid from wind turbines and photovoltaics.

It is, however, expensive and risky to assess the benefits of a solution by executing it in practice. Instead, modelling and simulation can be used to set up a virtual test environment in which the system can be analysed, and changes can be made, ranging from major structural modifications to minor parameter adjustments, and tested with relative ease and at low cost and risk.

When a specific consumer group is offered to buy or adopt a product or service, the consumer group can be divided into a number of categories depending on when (and if) they adopt. Figure 1 shows Everett Roger's adoption curve, for a group of consumers whose adoption behaviour follows a normal distribution [5]. The purpose of dividing the adopters into categories is to analyse and determine the characteristics that are prevalent within the individual categories and thereby obtain a conception of the consumer groups which the product or service should focus on.

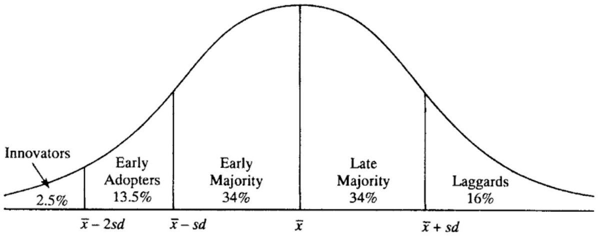

Figure 1: Classification of adopters depending on when they adopt [5]

The Danish Water Distribution System (WDS) contains many water towers used for pressure regulation and water reserve capacity for peak demand. However, common practice today is to let the pumps that fill these tower operate without paying attention to the electricity price or grid conditions [6]. Demand response might therefore present a potential for monetary savings on pump operation for the WDS operator and savings on grid maintenance and extension for the electricity grid operator. Using the previously described concepts, the characteristics of the pumps that will gain the most benefits from switching from operation without considering the electricity price to operation with implicit demand response based on the price signal.

Two main questions will be answered by simulating a population of water towers and pumps:

1. "For which water tower and pump design will it be most economically viable to switch from a conventional pump operation logic without demand response to an operation logic with an automatic implicit demand response control system, given that the water tower operator already pays a flexible electricity price that follows the spot market?"
2. "What is the optimal investment cost of the switch, if doing so must be viable for at least 50 % of the population, given a ROI time of 5 years?"

The paper is structured as follows: Sec. II contains an overall description of the water distribution system domain. Sec. III gives an in-depth description of the simulation framework on a generic basis, i.e. without considering the WDS. Sec. IV presents the model used in relation to the WDS domain along with the inputs and assumptions that are used for the simulation. Sec. V describes the simulated cases along with their results and discussion of those. Finally, Sec. VI concludes the paper.

II. SYSTEM DESCRIPTION

The system that is considered for the simulation is a component in a WDS. A simple form of a WDS consists of a raw resource, e.g. a river, lake or a groundwater reservoir, from which the water is extracted. It is then transported to a water treatment plant to be processed into drinking water. Afterwards, the water is transported through the water distribution network to the consumers. The network typically contains some water storage reservoirs. These are used for pressure regulation, water reserve capacity for peak demand and fire emergencies and to even out peak loads on the treatment plant to make it operate more efficiently [6, 7].

III. SIMULATION FRAMEWORK

The simulation is created using the simulation modelling tool, AnyLogic [8]. This platform supports system dynamics, discrete-event and agent-based modelling methods. The agent-based part of AnyLogic provides the tools needed for the model, as this study considers the investigated system as a population of agents with sub-components that are defined as agents as well. Furthermore, AnyLogic provides useful elements for visual representation of parameters and variables within populations, such as the one investigated in this paper.

A crucial aspect of the simulation model used in this study is its ability to be used for different similar domains with only few modifications. Therefore, a generic framework design is used in which the simulation is split into three main components: the domain logic module (DLM), the decision module (DM) and the business solution module (BSM). These three modules handle individual roles and tasks within the simulation and act relatively independently, using inputs from other modules sent through messages. In AnyLogic, the three modules are defined as separate agents as this method fits well with the functionality of the program and the notion that the modules independently behave according to their own sets of rules. The overall structure of the simulation and the message links between the modules are shown in Figure 2. The responsibilities of the individual modules are as follows:

The DLM contains all the characteristics that constitute the investigated domain system, i.e. a representation of the system mechanisms that apply regardless of the currently active business solution(s). It typically includes the core operation of the system and simulates the physical system. In short, the DLM includes the following:

- Physical system representation of the domain, including current state
- Boundaries that cannot be violated, either due to physical constraints or requirements for operation

The BSM represents the business models that the domain is subject to. This module consists of a number of sub-modules, one for each business solution that the operator/costumer can choose between. Each sub-module contains the cost structure and operation recommendation logic of its respective business solution. The module continuously determines when it is appropriate for the system to operate based on operation costs, e.g. electricity pricing, and other relevant factors. It then continuously sends an on/off message to the DLM. This message should be seen as a recommendation in that it might be disregarded by the DLM if any of the domain constraints are violated by complying to the message. For instance, the BSM might decide that a water tower pump should operate due to very cheap electricity prices at a given time and send a start signal to the DLM. However, if the tank is full at the given time, the DLM will override this decision and keep the pump turned off to prevent an overflow situation.

The operation logic found within a distinct business solution typically reflects the behaviour and decision making of an automated control system that might be included in the specific business solution or the system operator if manual operation control is employed instead.

Apart from providing operation recommendations for the DLM, the BSM sub-modules also calculate accumulated total costs of their respective business solutions since the start of the simulation. This includes costs that are imposed when the solutions are adopted (e.g. one-time fees/investments) and used (e.g. monthly subscription or service charge per kWh). Finally, as the costs of the individual business solutions are to be investigated and compared, each BSM sub-module is assigned their own domain instance, i.e. the DLM simulates several parallel instances of the domain system, one for each business solution. In short, the BSM therefore handles:

- Operation recommendation based on cost structure and business model logic
- Accumulated costs
- Costs for adopting/using the solutions

The final module is the DM. The DM represents the decision logic that the system operator (or other responsible party) uses when deciding between the available business solutions. The DM compares the performance of the solutions by using relevant parameters from these, e.g. the accumulated cost. A decision function then determines whether or not it is viable to adopt another solution than the one currently used.

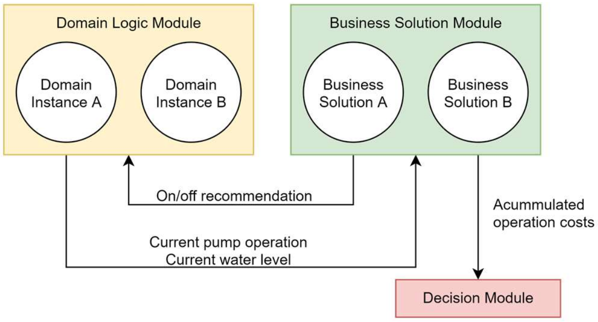

Figure 2: Overall structure of the simulation and its modules

The main advantage of using the separate module framework is the way it offers flexibility when used for different systems and/or different business solutions and decision processes. It is possible to change parameters and logic in one of the three modules without the necessity for considerable changes to the other modules. For instance, the modules might initially be set up to simulate a water tower pump as described in this study. However, if an industrial cooling system were to be simulated instead, it might be the case that the cooling operator is offered the same choice between business models as the water pump operator. If that is the case, the BSM can be left unchanged. If both operators make the adoption decision based on the same logic, the DM can be left unchanged as well. Naturally, there are differences between the physical operation mechanisms and constraints for the two systems, and the DLM will need to be changed accordingly.

While the three-module system proposed in this paper provide a generic framework that should be applicable for a broad range of domains within the energy and supply sectors, some domains might require the addition of new types of modules. What the characteristics and tasks of these modules might be is beyond the scope of this paper, but anyhow they should comply with the existing methodology of the simulation, i.e. be defined as independent agents that interact with the environment and the other modules through messages.

IV. EXPERIMENTAL DESIGN

With the generic framework of the model in place, this section considers its use for the water tower pump domain.

A. General Assumptions

The size of the pump population is set to 100. The only active stakeholders are currently the pump operators, while other actors on the system, e.g. electricity retailers and transmission and distribution system operators affect the pump operators through the electricity price. These actors are not affected by the conditions in the model and are not explicitly included as well and are therefore not considered stakeholders within the scope of the simulation. Future studies might include them, however. Electricity prices and water consumptions are not assumed to change over the years in the simulation, even though this might very well occur in practice.

B. Domain Logic

The AnyLogic system dynamics tool is used to simulate the current water level in the tank. As shown in Figure 3, there are two instances of a water tank, one for each business solution. The water is pumped into the tank from an unlimited source, as the treatment plant is assumed to be large enough to always provide enough water to the pump during operation. Furthermore, the water is subtracted from the tank into the block to the right which represents the consumers and keeps track of the total amount of water consumed during the simulation.

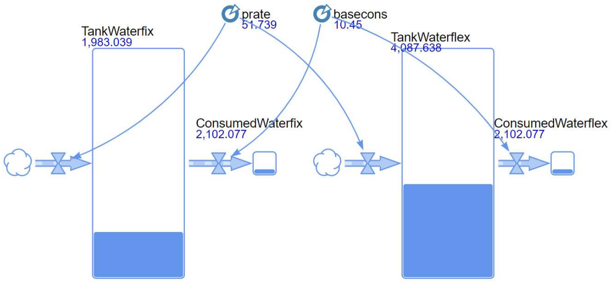

Figure 3: DLM Water tank representation in AnyLogic

The population of water towers contains a set of parameters that consists of:

- Water tank volume (m^3)
- Water tank elevation (m)
- Pump rate (m^3/h)
- Pump shaft efficiency
- Base water consumption (m^3/h)
- Water consumption profile

As the focus of this paper is the operation planning and business solution decision aspects of the domain, some properties are omitted from the scope of the simulation. This includes hydraulic characteristics in the water distribution system, components in the WDS that are outside the vicinity of the water tower and the operation of the water treatment plant (unlimited water supply for the pump is assumed). Furthermore, no leakages are assumed to occur in the system and there is no downtime for maintenance and equipment failure. Finally, the pump always operates at the same rate, efficiency and electricity consumption when on, and it can run for an indefinite period of time and switch on and off freely without any cooldown periods or extra costs.

The only boundaries used for the domain tank capacity are caused by the tank capacity; if the water tank is full, the DLM stops the pump, and if the tank is empty while a water demand is present, the DLM starts the pump. For this paper, however, as explained in the subsequent business solutions section, none of the two business solutions are able to make operation recommendations that violate the DLM boundaries.

The parameters of the domain are set as follows: The capacities of the tanks are defined according to a truncated distribution with min. 1000 m^3, max. 20,000 m^3, mean 6000

m^3 and spread 3000, based on 12 towers operated by Helsinki Region Environmental Services Authority (HSY) [9]. The tank capacities are excluding capacity used for fire emergencies, filter cleaning, etc. It is therefore considered possible to employ the entire volume of the tanks for flexibility purposes.

The water demand of the consumers connected to a specific water tower is based on the base hourly demand and the water consumption profile which features a set of time-dependent factors to be multiplied with the base demand. The base demand is set according to a truncated normal distribution with min. 12.8 m^3/h, max. 763.6 m^3/h, mean 109.2 m^3/h and spread 80. These values are based on a list of 57 Danish water supply districts [10] where the number of persons connected to a specific district is divided by the number of water treatment plants to find the number of persons per treatment plant (assuming that there is one water tower/reservoir per treatment plant). The 12 Helsinki water towers can contain a total of 106,300 m^3 which is approx. 40 % of the average daily Helsinki water consumption [9]. Given a population of approx. 1,495,000 in the Helsinki metropolitan area [11], this makes for an average hourly water consumption per person of 0.0074 m^3. Multiplying this value with the number of persons connected to the water district population, the values in the pre-mentioned normal distribution are obtained.

It is difficult to create individual water consumption profiles for the water towers in the population, as a profile is based on the types of consumers connected to the WDS. For instance, an industrial district will feature a significantly different load profile than a rural district with a majority of single-family homes or an urban district with a majority of apartments and commercial consumers. A generic profile that approx. captures the average of the different consumer types' load profiles found in [12] is used for the entire water tower population. This schedule is given in Table I. Monthly and seasonal variations are not very prevalent for any consumer types apart from vacation homes [12] and are therefore omitted.

Table I: Water demand factors at different times of the day for weekdays and weekends

Weekdays			**Weekends**		
Load factor	***Start time***	***End time***	***Load factor***	***Start time***	***End time***
0.5	00:00	05:00	0.5	00:00	07:00
1.0	05:00	07:00	1.5	07:00	14:00
2.0	07:00	09:00	1.0	14:00	22:00
1.5	09:00	17:00	0.5	22:00	00:00
2.0	17:00	20:00			
1.0	20:00	00:00			

The pumping rate is set in the same manner for the population as the base water demand. However, it is assumed in this study that the pump is always able to directly sustain the water demand in the system, and as such must be equal or higher than the maximum hourly water demand that might occur to prevent a situation where the water demand outpaces the combination of water storage and pumping rate. Therefore, the water pumping rate is initially set equal to the max. hourly water demand and is then multiplied by a factor to add additional capacity. This factor follows a truncated normal distribution, with min. 1, max. 5, mean 1.5 and spread 3.

For simplicity, the shaft efficiency of a pump is assumed to be constant regardless of the hydraulic state of the WDS. It is defined according to a standard range given in [13], where the average is 71.7 %. The tower height distribution uses an approx. average of the towers from [9], 45 m. Here, this height is considered the altitude between the pump (placed at ground height) and the water inlet in the tank. The position of the inlet is assumed to be at the top of the tank.

Finally, the electricity consumption of a pump is calculated using Eq. (1) [7], where Δh denotes the pressure head (set equal to the tower height), $\dot{V}$ denotes the pumping rate and μ denotes the shaft efficiency.

$$P_{pump} = \frac{\rho_{water} \cdot g \cdot \Delta h \cdot \dot{V}}{\mu} \qquad (1)$$

C. *Business Solutions*

Two distinct business solutions are included in the simulation: a conventional operation logic solution and an Implicit Demand Response Enabled Control System (IDRECS) solution with a flexible tariff. As explained in Section III, each of the business solution sub-modules is assigned a domain instance. They receive their current water level, used for operation planning/decisions, and pump operation state, used for cost accumulation, from the DLM. To better reveal the differences caused by the operation difference without interference from price differences, the two business solutions both use the spot prices for electricity costs.

1) Conventional operation logic solution

The conventional operation logic business solution uses a very simple logic for determining the on/off recommendation for the DLM: if the water reaches a certain predefined lower level, a start message is sent to the DLM. The pump then keeps operating until it has pumped enough water to reach an upper predefined level after which a stop message is sent. The two boundary levels are defined as percentages of the tank capacity; for this simulation, they are set to 0 % and 100 % for the lower and upper level, respectively, thus filling the tank all up when it becomes empty. The pump is therefore operated without paying attention to the electricity price.

2) IDRECS solution

The logic in the IDRECS solution sub-module is significantly more complex than for the conventional operation logic solution. The electricity spot prices are issued at 15:00 every day for the 24 hours of the day ahead (called a cycle) along with the total expected water consumption over these hours. The pump operator then proceeds to plan the operation for the cycle based on the available spot prices, the present amount of water in the tank and the expected water consumption profile. The planning must ensure that the water level in the tank is the same at the end of the cycle as at the start of the cycle, and the operator therefore determines the number of hours, *N*, that the pump must operate to exactly sustain the water consumption during the cycle. The estimated number of operation hours will almost never be whole and thus one of the planned hours will only feature operation for a partial amount of time, e.g. the pump might need to operate for 4½ hours to sustain the water consumption of a given cycle. The required hours of operation are assigned to the *N* hours of the cycle with the lowest spot prices. The incomplete (partial) hour will be assigned to the most expensive of the scheduled hours (i.e., the *N*th cheapest hour of the cycle). After the planning has been done, the cycle is simulated hour-by-hour. Through the on/off messages, the IDRECS business solution sub-component recommends the DLM to start the pump for a full hour at the beginning of an hour that exists in the operation schedule, unless the hour is the most expensive one in the schedule in which case partial operation is recommended instead. While the tank volume might be large enough for some pumps to always allow operation according to the schedule, some pumps might face situations where the schedule will either cause a tank overflow or a lack of water supply for the consumers. When the operation has been planned for a cycle and it begins, the following happens:

At the start of each hour, *h(a)*, during the cycle, the expected water consumption for that hour becomes known. The following list of conditions and actions is then processed:

1. If *h(i)* exists in the schedule set and it is not the most expensive hour in the set, the pump operates for 60 minutes of that hour. *h(i)* is then removed from the set. Condition 4 is an exception to this.
2. If *h(i)* exists in the schedule set and it is the most expensive hour in the set, the pump operates for *r* minutes of the hour. If the water level at hour start is less than the expected water consumption for that hour, the operation is placed at the beginning of the hour, otherwise it is placed at the end. *r* is then set to 60 minutes, and *h(i)* is removed from the set. Conditions 4 and 5 are exceptions to this.
3. If *h(i)* does not exist in the schedule set, the pump does not operate. Condition 5 is an exception to this.
4. When an hour begins, the available space left in the tank is determined as the empty space at the start of the hour plus the expected water consumption during the hour. If either condition 1 or 2 is true, but the available space is less than the volume that is planned to be pumped during that hour, the pump operates for the number of minutes that it is allowed to, given the available space. The operation starts at a point during the hour and continues until the hour ends, at which the tank will always be full. If condition 1 was true for *h(i)*, the minutes that could not be used for operation due to the lack of space are then added to *r* instead. If condition 2 was true for *h(i)*, the cheapest hour that has not already passed and is not already part of the schedule set is added to the set, and the number of minutes of operation is subtracted from *r*.
5. If the expected water consumption exceeds the water level at the start of an hour plus the volume planned to be pumped during that hour, if any, the tank will become empty and there will not be a sufficient water supply for the costumers. The number of operation minutes required for covering the water deficit is then subtracted from *r* and added to *h(i)*. Furthermore, if condition 2 is true, the already planned operation is moved from the end of the hour to the start.
6. If, at any time, *r* becomes negative, the most expensive hour in the schedule set is moved to the non-schedule set and 60 minutes are added to *r*.
7. If, at any time, *r* exceeds 60 minutes, the cheapest non-scheduled, non-passed hour is added to the schedule set, and *r* is subtracted by 60 minutes.

In the above statements, it is assumed that the tank capacity is no less than the hourly pumping rate so that a situation where both exceptions 4 and 5 are active cannot not occur.

In short, the pump operates as scheduled, unless this results in an overflow or a water deficit. If an overflow situation occurs, the pump operates as much as possible given the available space and water consumption during that hour (effectively leaving the tank full by the end of the hour) and moves the rest of the originally planned operation to a later hour. If a deficit situation occurs, the opposite happens, and operation planned for future hours is moved to the current hour to sustain the deficit.

D. Decision Logic

The water pump operator decides between the two business solutions based entirely on an economic viewpoint by looking at the return of investment that applies to the adopted solution. All pumps in the population initially use the conventional operation logic solution. However, as soon as the accumulated costs of the IDRECS solution plus the cost of adopting it is cheaper than the accumulated cost of the conventional operation logic solution, the pump operator will adopt. After the adoption has occurred, the operator is not allowed to switch back to the conventional operation logic solution.

V. CASE STUDIES

This study considers three main cases to investigate the different parameters' effects on the adoption rate. These cases are as follows (not to be confused with the conditions from the previous section):

1. All water towers are initially full
2. All water towers are initially half full
3. All water towers are initially empty

In all cases, the simulation is run from the beginning of 2017, and spot prices for 2017 and 2018 [14, 15] are used for the first two years of the simulation and are then recycled for the subsequent years. The 28. Feb. 2018 prices are used for the 29. Feb. 2020.

At first, the simulation is run for case 2, and after five years, the savings that the individual pumps would have gained by switching adopting at simulation start are added to a dataset. The median of the dataset denotes the investment cost that 50 % of the population members are willing to pay for the adoption, given a ROI time of 5 years. The investment cost is then included in the simulation, after which it is run for each of the cases to investigate how the three distributed parameters (tank capacity, base consumption and pumping rate) affect the adoption, and to compare the three cases.

The investment cost that results in a 50 % adoption share after 5 years in case 2 is determined to approx. 71,000 DKK. At this point in time, the pump operator that would have gained the smallest monetary return from the adoption (last adopter) is only willing to pay approx. 7,800 DKK, while the pump operator with the highest gain (first adopter) is willing to pay up to approx. 228,500 DKK. Running the simulation with cases 1 and 3 yield 50 % adoption at 9th of Dec. 2025 and 8th of May 2024, respectively. While it is quite coherent that both cases display slower adoption rates than case 2 (1st of Jan 2022) due to the flexibility limitation that are incurred by staying close to the water level boundaries, it is not entirely clear why case 3 features quicker adoption than case 1. It might be explained by the fact that the bulk of the water consumption lie late in the 15:00 to 15:00 cycle (see Table I) and after the relatively cheap night hours. This restricts the case 1 pump from exploiting the cheap hours very well due to the lack of free tank capacity. Meanwhile the case 3 pump is only forced to pump a moderate amount of water to sustain the water consumption in the late-afternoon and evening hours with unattractive prices, and then cheaply pump a lot of water during the night to prepare for the water consumption bulk in the morning and early afternoon.

The results reveal that the base water consumption has a positive effect on the adoption rate. This is simply due to the higher amount of water that must be pumped with higher demands, and thus the magnitude of the operation costs and thereby the savings gained from adoption increase as well.

The results furthermore show that the water tank capacity does not clearly affect the adoption rate. This makes sense due to the fact that the tank needs to be small enough so that the water level reaches both boundaries (empty and full) during the simulation and not only one of them. In this population, the average tank capacity is 56.6 times the magnitude of the hourly base water consumption (and approx. 1.95 times the max. daily water consumption). As the water level for the IDRECS solution must be the same every 24 hours, with a tank capacity able to contain 1 or more times the max. daily water consumption the water level will never become full if starting out empty or become empty if starting out full. For the half full case, the level cannot reach any of the boundaries if the capacity is at least double the max. daily water consumption (which the average capacity almost is, at 1.95 max. daily consumption). Even when the tank is small enough to become both empty and full during the simulation, this will still not necessarily happen very often. With the current simulation inputs, there is therefore no visible correlation between tank capacity and adoption rate, however, if the capacities were decreased significantly, it is expected that a correlation will emerge.

For the pumping rate, the rate is first divided by the base consumption due to the rate being based on the base consumption (as explained in Section IV.B.). After this is done, the pattern seems to be the same as for the tank capacity; no clear correlation emerges.

The next step for using the simulation should be to input a population of real water towers/pumps and find the ones that are most suited for the IDRECS solution. Furthermore, it could be interesting to introduce some uncertainties in the hourly water consumptions, i.e. let the expected water consumption become a little higher or lower when the water is consumed, thus causing the water level at the end of a cycle to be too low or high. Currently, the simulation will respond by adjusting the planned amount of operation for the next cycle to accommodate for the deviation.

VI. CONCLUSION

This paper shows the adoption behaviour of water pump operators who are offered to switch to a business solution with implicit demand response in the pump operation by simulating an artificially generated population of 100 water tower/pump pairs of different designs. It is found that an investment cost of 71,000 DKK will make it viable for 50 % of the population to adopt the solution with a ROI time of 5 years. Furthermore, the base consumption has a positive effect on the adoption rate, as pumps on water distribution systems with higher base consumptions have higher operation costs and thus can save more money by adopting the solution. The water pumping rate and tank capacity do not have any clear effects on the adoption rate, probably because they are too large in the simulation to represent any constraints with the two business solution operation logics.

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