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Testing the robustness of two water distribution system layouts under changing drinking water demand

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Abstract

The drinking water distribution system (DWDS) is a critical and a costly asset with a long life time. Drinking water demand is likely to change in the coming decades. Quantifying these changes involves large uncertainties. This paper proposes a stress test on the robustness of existing DWDS under changing drinking water demands. The stress test investigates the effects of extreme but plausible demand scenarios on the network performance. Two layouts, one conventional looped designed for fire flows and one designed as a self-cleaning, were tested. For twelve demand scenarios, diurnal patterns were simulated with the end-use model SIMDEUM. The performance of the network was evaluated on three criteria: i) network pressure, ii) water quality and iii) continuity of supply. Although the self-cleaning layout had higher head losses, it performed better regarding water quality than the conventional layout. Both networks are robust to the extremities of drinking water demands. The stress test is useful to quantify the performance range of the DWDS. For non-Dutch locations, the criteria and scenarios can be adapted to local conditions.

Introduction

Modern societies increasingly depend on water infrastructure to provide essential services that support economic prosperity and quality of life. The drinking water distribution system (DWDS) is one of the most critical infrastructures. The purpose of the DWDS is to supply water of good quality at adequate pressure and flow. Four design parameters for a DWDS are (1) a minimal pressure, (2) sufficient continuity of supply, (3) meeting the actual drinking water demand and (4) the fire flow demand. Based on these criteria, conventionally a design is made with a looped layout of the network (Vreeburg 2007). In conventional distribution networks, the velocities are low because the design is mostly dominated by the fire flow demands.

In the last 15 years, the concept of “self-cleaning networks” has been applied in the Netherlands (Vreeburg 2007). For the design of self-cleaning networks, unidirectional flow is required and a fifth criterion is added: the daily maximum flow velocity (DMFV). The DMFV is the maximum flow velocity that occurs daily for at least a few minutes. A pipe has a self-cleaning capacity when the DMFV surpasses the criterion value of 0.20 – 0.25 m/s to re-suspend particles that were allowed to settle during low flow periods (Blokker 2010). This criterion leads to a more branched system with shorter pipe lengths, smaller pipe diameters, higher flow velocities and shorter residence times (Vreeburg 2007 and Vreeburg *et al.* 2009). This design leads to less need for flushing and a reduced discoloration risk (Vreeburg *et al.* 2009).

The future water demand is an important input when designing a DWDS. Traditional planning processes begin with the selection of a future condition that is perceived to be the most likely to occur or the most conservative one. Planning is completed under that assumption, i.e. a single-scenario approach. This results in a single optimal design of the system. DWDS networks are constructed to provide service for at least 50 years. In this period of time, changes in water use and users’ routines occur driven by complex changes in technology, infrastructure and regulations, as well as economic and societal trends (Agudelo-Vera et al. 2014a). A single-scenario approach might result in a design that lacks the ability to maintain functionality over a large range of future conditions, so called robustness (Kang and Lansey 2013).

Changes in water demands affect the DWDS performance. Average demand reduction increases residence time, while peak demand determines head losses. It is unknown when these changes in demand will affect the functionality of the DWDS. In the last decades, several studies have proposed methods to design robust DWDS, among others Landsey et al. (1989), Kapelan et al. (2005), Kang and Lansey (2013), Basupi and Kapelan (2014), Marques et al. (2014), Jung et al. (2014) and Lan et al. (2015). These studies showed that robustness can be included in several ways during the design process. However further analysis is required to provide guidance on selecting appropriate threshold robustness values. Furthermore, these approaches are not suitable to test the robustness of existing systems.

In most developed countries, the DWDS is in place and it becomes progressively older, increasing the need for rehabilitation. Often during rehabilitation, the same pipe diameter is used to replace the old pipe. During the life time of the DWDS, at least five decades, water demand can significantly change. Agudelo-Vera et al. (2014) reported for the Netherlands a growth of about 30% of the daily water demand per person between 1970's and mid-1990's, followed by a reduction of 12% between mid-1990's and 2010. Therefore it becomes crucial to determine the robustness of the existing DWDS under changing demand to be able to guarantee a reliable water supply in the coming decades. Testing the robustness of the existing DWDS has not being done before. In this article the authors proposed a method which was tested for two networks layouts. Robustness can be measured by the variation of system performance (Jung et al. 2014). This study focused on existing DWDS and how to determine its robustness under, extreme, changing future water demand. A DWDS is robust if the changes in the performance due to changes in water demand can be counteracted by management measures without compromising its functionality.

Estimating the changes in water use and users' routines involves large uncertainties (Billings and Bruce 2011, Blokker et al. 2012, Fielding et al. 2012 and Willis et al. 2013). One of the most powerful and intuitive ways to deal with uncertainties is to use scenarios. Scenarios are alternative views of how the future might unfold. Therefore, scenarios are neither predictions nor forecasts of the future but a set of representative ranges of plausible futures (Kang and Lansey 2013). In this study, instead of trying to design with uncertain parameters, the robustness of the DWDS is tested by determining changes in the DWDS performance under extreme loads, a so called stress-test. A stress test can be defined as a form of deliberate intense testing to determine the stability or robustness of a given system. It involves testing beyond normal operational conditions in order to observe the results. In this article a stress test for the DWDS with extreme but plausible demand scenarios is proposed to quantify the range of variation of performance of the DWDS. This article builds on earlier research, where the future demand scenarios were defined and earlier tests were performed (Agudelo-Vera and Blokker 2014 and Agudelo-Vera et al. 2014b).

The objective of this paper is twofold. First to propose a method to determine the robustness of DWDS under changing water demand using a stress test and second to quantify and compare the performance and robustness of two types of network layouts. In this article the authors want *i*) to check if the robustness test is applicable to different network layouts and *ii*) to determine the influence of the network layout in the robustness of the network. Therefore, the same area was analysed using two different layouts. One layout is an existing conventional looped (CL) network build mainly between 1989 and 1997, in which the fire flows primarily determine diameters and layout. The other is a theoretical self-cleaning (SC) network for the same neighbourhood. The SC network was specifically designed for this research, with more unidirectional flows and smaller pipe diameters, primarily designed on high velocity and minimum residence time (Vreeburg *et al.* 2009). This study focuses on the distribution pipes used to supply drinking water to customers, e.g. the pipes in the streets.

Hence, transport mains are not included. The networks are tested considering changes in demand, reflecting different life styles and technological changes, or aging infrastructure.

Methods

The proposed Stress-test consists of seven steps. Fig**. 1** describes these steps and indicates the specifications used in this study. Each step is explained in the following sub-sections.

Fig. 1

Step 1: Define criteria and indicators

The development of criteria and metrics, or indicators, to assess water supply systems has been extensively described by Alegre et al. (2006). In this study a selection of objective indicators commonly used in the Netherlands was used to describe the performance of the DWDS. A DWDS has to comply with three main criteria: minimum pressure, adequate quality and continuity of supply. Table 1 shows the criteria and the indicators selected to determine the performance of the DWDS.

Table 1

Self-cleaning networks present advantages regarding water quality. However water providers are still concerned regarding: *i*) the ability to supply the firefighting water demand and *ii*) the reduction in the continuity of supply compared with traditional looped networks. In The Netherlands in 1999 it was agreed, with the national organisation of firefighters, a flow of 30 m^3/h as the minimum requirement for the primary supply serving the first attack of the fire brigade for residential areas with normal housing, meeting modern post-1950 fire codes. For older residential areas a fire flow of 60 m^3/h was used for network design (Vreeburg 2007).

The design for fire flows is done considering no additional water demand. Hence, meeting fire flows requirements is independent of the changes in demand, which are the focus of this study. Consequently, continuity of supply is included in this analysis, but fire flows not.

Minimal pressure

In the Netherlands the water companies have to provide water to the customer with a pressure of at least 150 kPa after the water meter at 1 m^3/h flow (Drinking Water Decree 2011). Pressure can be easily adjusted at the pumping station, and therefore head losses in the network were used as a surrogate indicator for pressure. The head loss was analysed only for the non-zero demand nodes. The maximum head loss (m) per scenario was determined by subtracting the minimum head of each node, out of the 30 simulated diurnal patterns, of the available head at the feeding main. In this study a fixed head was used to determine the maximum possible head losses for this system under changing water demand. These losses were weighted by number of connections per node to describe the maximum head loss in the network. The 99^{th} percentile of the maximum head loss in the network was used as maximum head loss per scenario.

Water quality

Water quality may change during transport and distribution. In this study, the water quality is quantified using two surrogate variables, maximum residence time and self-cleaning capacity of pipes as defined in Table 1. Residence time is an important aspect of water quality in a DWDS as it influences bacterial regrowth, corrosion, sedimentation and temperature. More specifically, the maximum water age (or residence time) is most important (Machell *et al.* 2009). However, there are no guidelines for the maximum travel time as it is not yet clear how exactly the water quality deteriorates over time. In this study, the maximum residence time for each pipe, from the 30 simulated patterns, was determined per scenario. After that, the maximum residence time of the network was determined by weighting the selected maximum residence time by the length of each pipe. The 99th percentile of the residence time in the network was selected as maximum residence time per scenario (τ_{max}).

In the DWDS two categories of pipes can be identified based on their functionality: transport pipes and distribution pipes. Transport pipes have large diameters and no (or very few) direct supply connections and their main purpose is to ensure high continuity of supply. Flow in transport mains is mainly turbulent with typical maximum flow velocities of 0.5 – 1.0 m/s (Vreeburg 2007). While, distribution pipes have smaller diameters and they supply directly to customers. Under normal operating conditions, the maximum flow velocities in distribution mains can be very low (smaller than 0.01 m/s) and change rapidly. Flow directions may reverse and residence times may be as long as 100 hours due to stagnation (Blokker 2010). The self-cleaning design is only applicable to distribution pipes and leads to pipe diameters of typically 100 mm and smaller. Distribution pipes larger than 100 mm often have fewer or no connections, have a different function, and are not designed to have a self-cleaning capacity. Therefore, the self-cleaning capacity is determined only for the distribution pipes with a diameter smaller than 100 mm. A pipe has a self-cleaning capacity when the median of the maximum flow velocity (v_{mm}) is larger than 0.20 m/s (Blokker 2010). For this analysis a small hydraulic time step, typically smaller than one minute, is required. The daily maximum velocities of each of the 30 diurnal simulations per pipe segment per scenario were selected. After that the median of the daily maximum velocities was calculated. To describe the self-cleaning capacity of the network the median velocity per pipe segment was weighted by the length of each pipe segment, for the pipes with a diameter smaller than 100mm.

Continuity of supply

The continuity of supply describes the system performance under failure conditions. The continuity of supply is reflected in the number of connections that are cut-off due to failure in combination with the time needed to repair the failure and get the service back on (Vreeburg et al. 2009). The continuity of supply is evaluated using the Customer Minutes Lost (CML). CML is defined as the average number of minutes per year that a customer does not receive water. CAVLAR (Criticality Analysis Valve Locations And Reliability) software is used to calculate the CML of each network based on the failure rate of the pipes and the valve reliability (Blokker *et al.* 2011b). Using as reference the data reported in Blokker *et al.* (2011b), a failure rate of 0.05 failures per km per year, duration of interruption per failure of 180 minutes and valve reliability from 75% to 100% are used as input parameters. Although CML is independent of the demand scenarios, the analysis of the variation of the valve reliability gives an indication of the robustness of the network layout under different maintenance strategies.

Step 2: Define scenarios

In this study two levels of stress are applied: medium stress (MS) scenarios and high stress (HS) scenarios. MS scenarios are the four future scenarios for 2040 proposed by the planning agencies in the Netherlands for 2040: Regional Communities (RC), Strong Europe (SE), Global Economy (GE) and Transatlantic Markets (TM) (Janssen *et al.* 2006). The four scenarios emerge from variation along two axes; one is the extent to which the government stimulates free market forces, the other is the international orientation, or the extent to which the borders and economy are open for international influences. The implications of these scenarios on residential drinking water demand are described by Blokker *et al.* (2012).

Additionally, eight HS scenarios were defined during a workshop held with representatives of two Dutch water companies. HS scenarios were defined by a combination of different feasible factors based on the MS scenarios and also based on the current situation (Now) combined with adoption of technological developments. Although it is known that full adoption of new water appliances may take several decades (Agudelo-Vera *et al.* 2014a), HS scenarios consider for instance 100% of penetration of new technologies, such as vacuum toilets (1 L per flush), dual systems for non-potable demand, or luxurious showers. Not only technological changes influence drinking water demand. Therefore, scenarios considering diminishing of the population (DP) and increasing leakage rate due to aging of infrastructure (Leak) were analysed. The twelve scenarios are briefly described in Table 2, MS are scenarios 1-4 and HS are 5-12. In the Netherlands non-revenue water is about 5%, this includes losses due to leaks, cleaning losses, firewater and measuring differences (Vewin 2013). Therefore, the losses due to leaks are lower than 5%. The authors have assumed zero leakage for all the scenarios except for the scenario "Leak".

Table 2

Step 3: Select networks

A residential area in the south of the Netherlands was selected for the case study. Two network layouts, one CL (existing) and one SC design (theoretical, specially designed for the purpose of this project), were considered. Only distribution pipes were considered, the maximum diameter in the layouts is 200 mm. The characteristics of the networks are shown and described in Fig. 2 and Table 3. The CL layout was designed considering a fire flow of 60 m^3/h while the SC layout has been designed to supply a fire flow of 30 m^3/h and with a maximum section size of 100 connections.

Fig. 2

Table 3

For the scenario "Now", specific household statistics for this location were used. The studied area has 1019 residential connections. Statistics Netherlands (CBS 2013) gives information about the number of households per district. Three household types are distinguished, viz. one-person households, two-person households and families with children. For every household type, the number of people, the fraction of men and women, and the division over the different age groups is given in Table 4. Table 4 and the input data regarding penetration rate and end-use sub-type information (frequency, duration and intensity) are based on the average information available for the Netherlands (Blokker *et al.* 2010). For the other scenarios the household composition is described in Blokker *et al.* (2012). The changes in penetration, frequency, duration and intensity and diurnal patterns are based on Blokker *et al.* (2012).

Table 4

Steps 4 & 5: Simulate drinking water demand and run hydraulic model

In this study the end-use model SIMDEUM (Blokker et al. 2010) was used to generate diurnal demand patterns. SIMDEUM is a simulation model for residential water demand patterns on a small temporal scale (1 s).SIMDEUM uses a "bottom-up" approach of demand allocation. This means that a unique stochastic drinking water demand pattern is constructed for each demand node by summation of the individual household's drinking water demand patterns. SIMDEUM uses statistical information as well as information regarding end-uses, allowing the simulation of changes in technologies and in user behaviour.

SIMDEUM is based on stochastic information on end-uses and it has been validated in different studies in the Netherlands. These validations include daily water demand, peak demand, pattern shape and the frequency distribution of flows and accelerations in flow (Blokker et al., 2010b) and residence times (Blokker et al. 2010a and Blokker et al. 2011a). Therefore, it was assumed that SIMDEUM would generate realistic water demand patterns for the studied DWDS.

Thirty diurnal patterns were simulated for each of the twelve scenarios and for each connection with SIMDEUM. These patterns at a time step of on one second were aggregated to a time step of 5 minutes to analyse peak demand, head losses and residence time, and to a time step of 36 seconds (0.01 h) to analyse the self-cleaning capacity. The two networks were simulated for a three day period, with a repetition of the diurnal pattern, using EPANET software (Rossman 2000).

Steps 6 & 7 Determine variation range of the criteria and discuss results

First the performance of two networks was determined for the current situation (scenario Now) using the selected criteria and indicators. After that, the performance under twelve future demand scenarios was determined. Finally, the robustness was assessed by comparing the performance of the DWDS under the future demand scenarios against the performance of the DWDS under the current demand. The robustness was discussed with a panel of experts. A network will be robust if the changes in the performance can be counteracted by operational measures. The following sections describe per criteria how each criteria was evaluated.

Results and discussion

Daily drinking water demand (DDWD)

Each demand scenario was characterised by the average DDWD (m^3/day) and the peak demand (m^3/h).

Daily water consumption

The average DDWD in litres per capita (lcd) for each scenario and for each end-use is shown in Table 5, as well as the household size (HHS) per scenario. The current DDWD per capita is 142 lcd (scenario Now) and the current average household size is 2.5 persons. The range of variation of the DDWD per capita in this study was a minimum of 47 lcd. – a 67% reduction – for the "Eco+" scenario and a maximum of 198 lcd. – a 39% increase – for the "Lux." scenario. The current average DDWD in the network was about 360 m^3. Due to variations of household size per scenario the range of variation of the average DDWD of the MS scenarios is 247 m^3 and 304 m^3, which is a reduction of 16% and 32%. For the HS scenarios the range of variation was 143 m^3 – 509 m^3, about 60% reduction and a 40% increase.

Peak demand

The peak demand (Q_{max}) of each scenario was determined by selecting the maximum flow of the 30 simulations at each simulated time step, each five minutes. The reported Q_{max} was the 99% percentile of the maximum demands. For the current situation, Q_{max} was 49 m^3/h. Fig. 3 shows the variation of the daily demand and the Q_{max} for the different scenarios. The MS scenarios showed a reduction in the average daily demand and on the Q_{max}. The range of variation of the Q_{max} for the MS scenarios was a reduction of 18% to 31%. While, the HS scenarios showed peak variations between -57% and 39%. The most extreme scenarios are "Lux." and "Eco+". Moreover, in general there was a strong positive correlation between average daily demand and peak demand. For the majority of the scenarios it was found that the peak was approximately 3.3 times the average hourly demand. It was difficult to define a plausible scenario with a high average demand and low Q_{max}, or with a low average demand and a high Q_{max}. The "Leak" scenario and "Lux_Dual" came closest.

In this study, a special set of scenarios was used because the scenario "Now" has a relative high water demand and a relative large HHS for the Dutch case. In this region shrinking of the population is expected. Therefore, almost all the scenarios have a smaller household size, resulting in a lower future total water demand for this neighbourhood than the scenario 'Now'. Only the "Leak" scenario is based on Now. Note that the total demand is influenced by the total daily consumption per capita multiplied by the number of households and the household size. The number of households was the same in all the scenarios while the household size changed. Only for the diminishing population (DP) scenario a reduction of 30% in the number of households was assumed.

Table 5.

Fig. 3.

Fig. 3 shows that RC and GE are the extremes of the MS scenarios, and that "Lux." and "Eco+" are the extremes of the HS scenarios. These four scenarios were selected to determine the ranges of variation of the two stress levels in the following subsections.

Network performance

Fig. 4 shows the results of the three different performance criteria for the two layouts and for the situation "now" and the 12 demand scenarios.

Fig. 4.

Head loss

Fig. 4a shows the maximum head losses per scenario for the two network layouts in relation to the peak demand. Fig. 4a shows a positive correlation between peak demand and maximum head loss. However, in the "Eco+" scenario, the difference is minimal. In general, for the same peak demand (same scenario), the head losses are higher in the SC layout. Two main characteristics were observed. Firstly, as expected, the SC layout with shorter lengths and smaller diameters than the CL layout had larger head losses. For the current situation, the maximum head loss of the SC layout was 2.2 m., while of the CL layout was 0.9 m. Considering all the scenarios, the maximum head losses of the SC layout varied from 0.4 m to 3.0 m and the maximum head losses of the CL layout varied from 0.3 m to 2.1 m. Secondly, the "Lux." scenario had the largest head loss for both network layouts, while the "Dual" and "Eco+" scenarios showed to have the smallest head losses. The maximum head loss found was 2.97 m for the "Lux." scenario in the SC layout. This head loss appears in the periphery of the network and could be compensated by increasing the head in the transport network. Therefore the head loss does not represent a threat for the functioning of the network.

Fig. **5**(a and b) show the cumulative distribution function (CDF) of the head loss in the networks for five selected scenarios. For the CL layout in the current situation 90% of the connections had less than ca. 0.5 m. of head loss, while for the SC layout 90% of the connections had less than ca. 1.0 m of head loss. In the CL layout, the head losses showed less variation than in the SC layout.

Fig. 5.

Water quality

Fig. 4b shows the comparison of the results of the water quality indicators for the two networks for the two levels of stress. A clear difference is found between the two network layouts, where the SC layout performs better under all scenarios compared with the CL layout with shorter residence times and higher percentage of self-cleaning capacity.

Maximum Residence time

The values of τ_{max} showed differences between the scenarios and network layouts. Fig. 4b shows the maximum residence time for each scenario for the two layouts. For the CL layout, τ_{max} was almost two days. For the SC, τ_{max} was 1 day. For the CL layout, it varied from 1.4 till 3 days, while for the SC layout it varies between 0.8 and 2.4 days. This may have an influence on water quality. Note that there is also a residence time from the production station to the beginning of the tested network. In this case this residence time was estimated as less than 2 hours – storage time in tanks was ignored, but in other cases this may be larger and significantly influencing the water quality. In the CL layout, ten scenarios showed τ_{max} larger than two days, while in the SC layout only two scenarios had τ_{max} larger than two days.

Fig. **5** (c and d) show the CDF of the residence time of network. In general, the residence time increased with respect to “now” for the “ECO+” scenario, while the residence time decreases for the “Lux.” scenario. Fig. **5** (c and d) also show that in the extreme scenario “Eco+”, the 90th percentile was ca. 2.5 days for the CL layout, for the SC layout it was about half a day. Fig. **5** (c and d) show that for the CL layout there is a clear difference between the MS and the HS scenarios in network performance. This difference is less strong in the SC layout, in which smaller differences are found between the current situation, the MS scenarios (GE and RC) and the HS scenario “Lux.”.

Self-cleaning capacity

The v_{mm} was used to determine the self-cleaning capacity of the network, for the pipes with a diameter smaller than 100 mm. The pipe had a self-cleaning capacity if v_{mm} was larger than 0.20 m/s. To describe the percentage of self-cleaning pipes in the network, the length of the net which has a minimum velocity (m/s) was used. For the current situation, 6% of the length of the network – with small diameters, in the CL layout has a self-cleaning capacity, while this percentage is 68% for the SC layout. For the twelve scenarios the self-cleaning capacity varies between 2% and 11% for the CL layout and between 25% and 89% for the SC layout. The “Eco+” scenario represents the worst case for the looped network, and the “Dual” scenario represents the worst case for the SC layout. Velocity in the pipe is equal to the flow divided by the cross-sectional area of the pipe. Thus, for a given cross-sectional area, a reduction in the flow results in low velocities. Comparing the characteristics of the two layouts, the SC layout has a smaller cross-sectional area than the CL one. For the SC layout, only in the ‘Dual’ scenario the current pipe diameters are too large resulting in flow velocities that are insufficient for self-cleaning pipes. For this scenario, the network would need to be cleaned resulting in an increment in maintenance cost. For the CL layout cleaning of the network is required for all the scenarios.

Fig. **5** (e and f) show the CDF of the v_{mm} for pipes with a diameter smaller than 100 mm. It is important to consider that in the CL layout 51% of the length has diameters smaller than 100mm, while in the SC layout 63% of the length has diameters smaller than 100mm, Table 1. This means that even a larger portion of the SC layout is self-cleaning compared to the CL layout. Fig. **5** (e and f) show that for the CL layout in the worst case "Eco+", the maximum self-cleaning capacity was about 2%, while for the SC layout this percentage was 25% for the Dual scenario. In the CL layout, the low velocities allow settling of particles, and therefore, cleaning of the network is needed. For the SC layout the percentage of the self-cleaning capacity is 50% higher, except for the "Dual" scenario, resulting in lower operational costs related to flushing the network. This cost reduction should be compared to the incremental costs of pumping, which was out of the scope of this study because the relation between flushing frequency and self-cleaning capacity is still unknown.

Customer minutes lost

Interruption of supply expressed in Customer Minutes Lost (CML) per year was calculated per network, independent of the demand scenarios. Fig. **6**a shows the variation of CML for different valve reliability values, considering equal conditions on failure rate and repair time. A comparison of the CML has to consider the differences in layout, section pipe length, customers per section and number of valves, see Fig. **6**b. The number of valves has decreased considerably in the SC layout, resulting in average larger sections compared with the CL layout. Thus when a valve fails and a section cannot be isolated successfully, a larger number of customers will be affected than in the CL layout. A reduction of number of valves by a factor of 5.4 only represents an increase of a factor of 2.6 of the CML. A limited number of valves facilitates maintenance and controllability, which is related to improved valve reliability, reducing costs and limiting CML. A CML of eight minutes in the CL layout network requires a 75% valve reliability for 140 valves, while a comparable CML in the SC layout requires a 90% valve reliability of only 26 valves. Van Thienen et al. (2011) reported for the Netherlands a range of valve maintenance frequency between once every 10 years and once each year. For the two studied networks, if valves of the CL layout are maintained once in 10 years, this means, 14 valves per year. While a maintenance frequency of once in three years means 9 valves per year for the SC layout. Therefore, even with a three times higher maintenance frequency the costs of maintenance of the SC layout are still lower.

Fig. 6

Performance, robustness and operability

A network is robust under changing water demand if the changes in the performance can be counteracted by operational measures. Fig. 7 shows the ranges of variation of the performance of the networks under changing demand. The analysis of these networks showed that neither the medium stress scenarios nor the high stress scenarios posed a threat to the performance of the DWDS, assuming sufficient availability of water at source. The two networks were robust under extreme changes of the water demand, maintaining its functionality by adapting the operations in the pumping station to compensate changes in head losses or by flushing the network to compensate changes in residence time.

Water suppliers operate within constrained budgets, while being expected to deliver quality service at a low price, meeting sustainable standards, e.g. energy consumption, materials use, etc. For this specific case, the maximum head loss - of one meter - can be compensated by increasing the pressure in the network, without representing a risk of increasing leakages. For larger and more complex networks the impact of changes in the network pressure can result in problems of too much pressure in some zones of the network and in higher occurrence of leakages (Greyvenstein and Van Zyl 2007). The costs and environmental impact of the extra energy use for pumping in the SC layout may be compensated by the reduced use of materials and less maintenance needed. This additional pumping is only needed during the peak demand, in average there is almost no difference. The SC layout has a reduction of 24% in pipe length (3.4 km), 45% in volume and 80% in valves, Table 3. Moreover, the self-cleaning capacity minimizes flushing of the network and reduces operational costs. A detailed analysis, such as a Life-cycle analysis (Du et al. 2013), a Life-cycle Energy Analysis (Prosser et al. 2013) or a Life-cycle Cost Analysis, is recommended as future research.

Fig. 7

Although the two networks are robust, the SC layout performs better regarding water quality, i.e. residence time and self-cleaning capacity, than the CL one. Those are critical parameters for water quality, especially in the Netherlands where water is distributed without chlorine (Van der Kooij *et al.* 1995). Given the uncertainty on how water quality deteriorates in the DWDS it is recommended to keep the residence time as low as possible and to try to increase the self-cleaning capacity of the DWDS. Then self-cleaning designs are preferred over conventional looped ones. For existing looped networks, where rehabilitation is distributed over time, the planning of this replacement offers possibilities for a transition from traditional looped to branched self-cleaning systems.

Although CML was higher for the self-cleaning design for the same valve reliability, this is compensated by the limited number of isolation valves, resulting in better manageability and controllability of the system. Calculating the CML requires a good knowledge of the valves location and status (open or close), and it requires to know the reaction time and the expected failure rate of the pipes. Once these data is known the CML can be improved by focusing maintenance on valves of critical sections (e.g. Sections with a large number of connections), (Blokker et al. 2011b).

Special attention should be given to the lack of boundaries and limits for the appropriate functioning of DWDS. Further research should focus on determining the maximum head loss or residence times allowed in DWDS. The threshold for maximum head loss should also consider the energy and costs to guarantee an affordable water supply. In the special case of non-chlorinated water more research is needed to determine limits for maximum residence times. The results obtained are case-specific and therefore they need to be further confirmed with additional tests.

The stress test approach presented in this article, using the broad range of scenarios, represents a useful approach to quantify the range of performance levels of networks under different operating conditions. Moreover, this approach can be used as a test during the design phase of DWDS to achieve a robust DWDS being complementary to other approaches e.g. phasing construction (Creaco et al., 2015). The end-use modelling of future scenarios allows to quantify plausible demand scenarios and to simulate realistic variations of peak demands. The studied area was a residential one; however a similar approach can be applied for other areas e.g. industrial or touristic. The demand scenarios are indicative, therefore other type of extreme demand scenarios could be defined, such as a new large consumer, or holiday peaks. The stress test methodology is independent of the scenarios. Tailor made scenarios should be always defined, preferable with representatives of the water companies. Future research can focus on robustness of networks where non-residential demands are present.

The test was applied for two networks in the Netherlands. Criteria were adjusted to the needs and local situation of the water company. In other locations different criteria can be added to evaluate the DWDS performance. For instance, in other countries where the leakage rate is a larger percentage of the demand, a more detailed approach to simulate the leaks is needed (Schwaller and van Zyl 2014). The test is also applicable with other boundaries or choices e.g. including pumping stations or using adapting pump operations (Zhuang, B. et al. 2013).

As mentioned our focus is on existing networks, especially in developed countries. An important consideration when evaluating existing networks that were designed decades ago is that design criteria and parameters are not always registered. The stress test is a tool to check if under various water demand scenarios a given network will fulfil an expected performance.

Although the stress test presented in this paper does not forecast when the changes in demand will occur, the two levels of stress can be interpreted as two time horizons, short and long term. A similar approach can be used for multiple time horizons and it can support decisions involving phasing of these network improvements. As stated by Walski (2015) the future never turns out exactly as planned and decisions are adjustable as the future reveals itself. Therefore we recommend to apply the stress test each 5 to 10 years to monitor the (expected) performance of the network.

This type of analysis is also relevant for other countries, for instance fast-growing cities where water demand is expected to increase in the coming years or areas with shrinking population.

Further testing of this approach can include larger and more complex networks. In this article the authors focused on testing the robustness of the system. Post-analysis can include the selection of critical nodes or pipes e.g. connections to hospitals, and determine the range of performance of these locations under changing demand.

Conclusions and recommendations

The stress test, which combines the scenario approach and detailed network calculations, is a useful approach to determine the range of performance of a DWDS under changing drinking water demand. This test showed that it is not needed to forecast in detail each change in drinking water demand. Hence, it is possible to test the robustness of an existing network by describing and modelling a range of customized and feasible scenarios. The stress test is a tool to check if under various water demand scenarios a given network will fulfil an expected performance. Existing networks will undergo improvements due to maintenance or repair needs. With the stress test it can be determined if changes in water demand are (can be) a driver for these improvements in the network.

The general conclusion of the studied case comparing two layouts is that the current conventional looped drinking water infrastructure is robust enough for the future drinking water demand scenarios, but with a need for frequent cleaning of the system. With respect to the water quality parameters, the self-cleaning design performs consistently better.

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TABLES

Table 1. Criteria to determine network performance

	Criteria	Indicator	Units	Remarks
1	Minimal pressure	Maximum head loss	m	Maximum dynamic head loss: difference between the feeding main and each node with at least one customer (under flow conditions)
2	Water Quality	Residence time	days	Determined in the pipes, τ_{max} = 99th percentile of the network weighted per length of the pipe section
		Self-cleaning capacity	%	Percentage of the network (in length) with a median of the maximum velocity, v_{mm}, larger than 0.20 m/s. determined in the pipes Ø < 100 mm.
3	Supply continuity	Customer Minutes Lost (CML)	Minutes / customer -year	Average minutes per customer per year with no supply due to bursts and repair

Table 2. Description of the twelve scenarios

Scen	Name	Characteristics
0	Now	Baseline: current situation. Frequency of Showering is 0.7 (day^{-1})
1	RC	Regional Communities: per capita demand declines because the economic downfall results in (water) saving behaviour, coupled with decreasing population. The average age of the population increases. Frequency of Showering is 0.8 (day^{-1}).
2	SE	Strong Europe: Despite low economic growth, mobility increases due to open borders. Personal hygiene habits have changed with an increase in shower frequency. Water pricing based on real cost drives alternative water resources to be adapted on a larger scale; e.g. rain water tanks for watering the garden. Frequency of Showering is 0.9 (day^{-1}).
3	TM	Transatlantic Market: Population growth causes increases in drinking water demand also changes in routines e.g. higher showering frequency. Innovations aim at luxury and wellness products. Frequency of Showering is 1.0 (day^{-1}).
4	GE	Global Economy: Economic growth causes increases in consumption. Innovations are aimed at luxury and wellness, people shower longer and water their garden more frequently to diminish the effects of climate change. Frequency of Showering is 1.0 (day^{-1}).
5	Dual	Toilet, laundry machine and outside tap are not supplied by DWDS.
6	Eco_RC	Based on RC with innovative sanitation concepts. 100% adoption of 1 L flushing toilets.
7	Lux.	Luxury, based on current situation with 100% adoption of luxurious shower (0.2 L/s).
8	GE+	Based on "GE" but with a frequency of 1.4 (day^{-1}).
9	Leak	Based on "Now" with leakage of 20%.
10	Lux_Dual	Based on "Now" with 100% adoption of luxurious shower with dual system for toilet, laundry machine and outside tap.
11	Eco+	Adoption of innovative sanitation concepts plus water use efficient showers, washing machines and dishwashers.
12	DP	Diminishing population: 30% reduction of the population in the area due to empty houses (not smaller households).

Table 3. Network characteristics for the networks studied

		CL layout	SC layout
Volume (m^3)		110	60
Length (km) :		14.2	10.8
Diameters distribution in km and (%)	< 100mm	7.2 (51%)	6.8 (63%)
	≥ 100mm	7.0 (49%)	4.0 (37%)
Number of isolation valves		140	26
Number of sections		96	24
Maximum section size (number of connections)		32	94

Table 4. Household statistics as used in the end-use model for the studied area

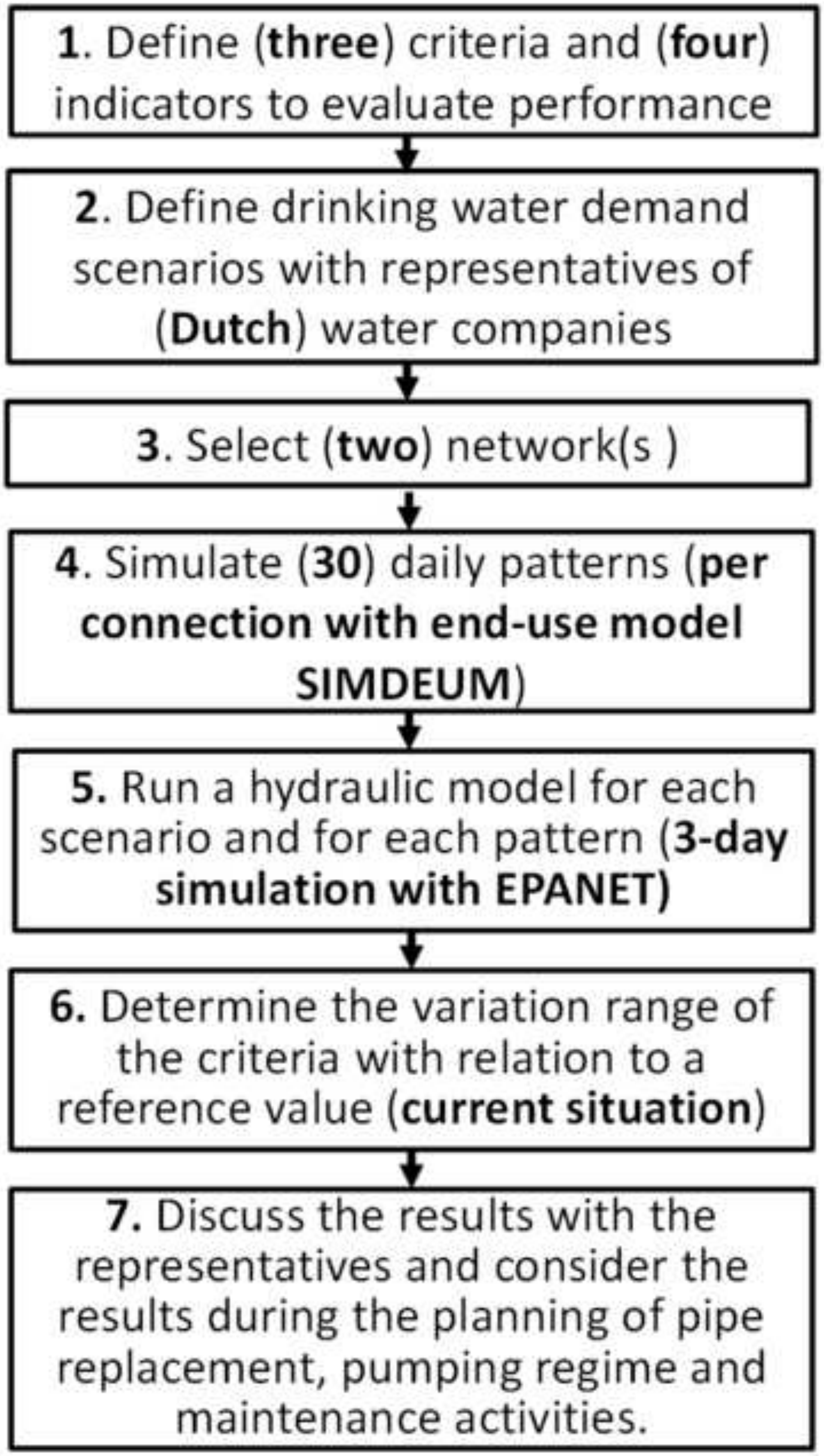
		One person households	**Two person households**	**Families with children**
Number of people per household		1	2	3.6 (on average)
Number of households (%)		24	29	47
Gender division: Male / Female (%)		58 / 42	50 / 50	50 / 50
Age division (%)	Children (0-12 years old)	0	0	31
	Teens (13 – 18 years old)	0	0	18
	Adults (19 – 64 years old)	82	82	51
	Subdivision: % of adults with out-of-home job		Both persons: 49	Both parents: 39
		Male: 67.5	Only male: 26	Only father: 52
		Female: 52.4	Only female: 6	Only mother: 3
			Neither person: 18	Neither parent: 5
	Seniors (> 65 years old)	18	18	0

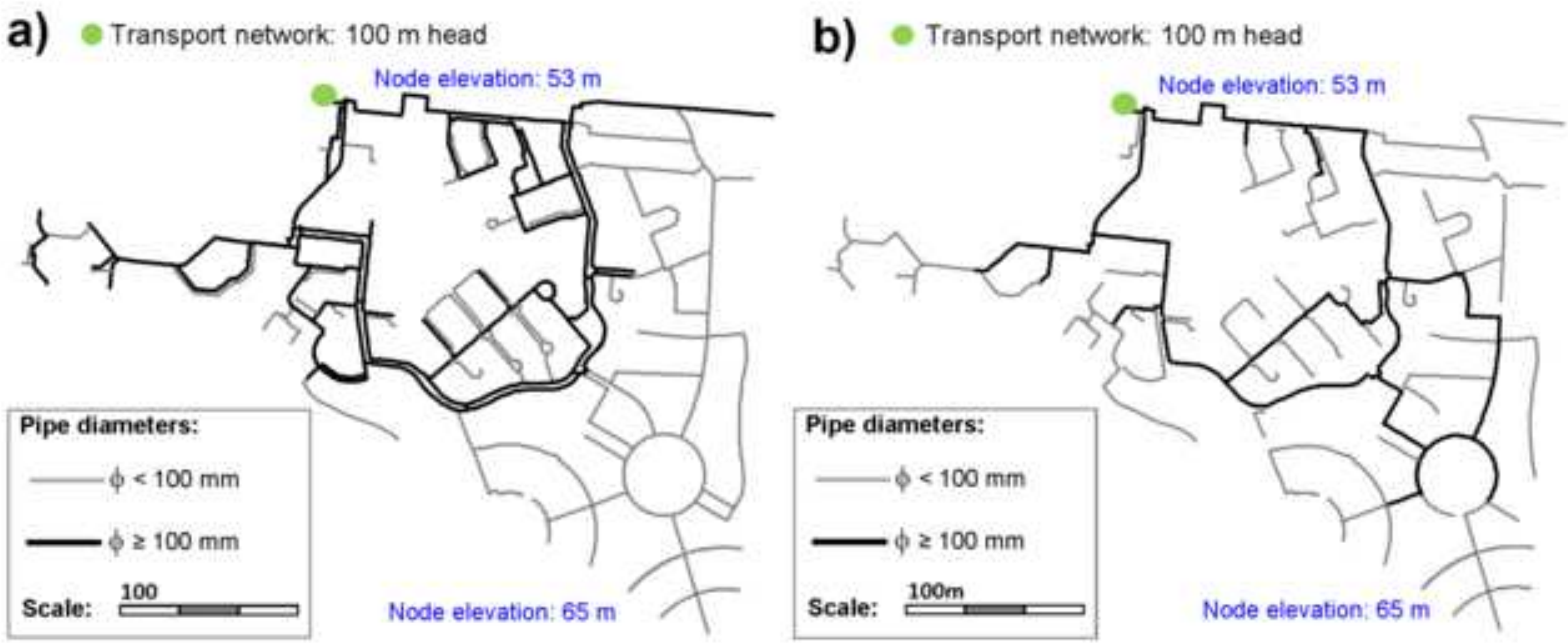
Table 5. Daily water consumption in litres per capita per day (lcd) per scenario.

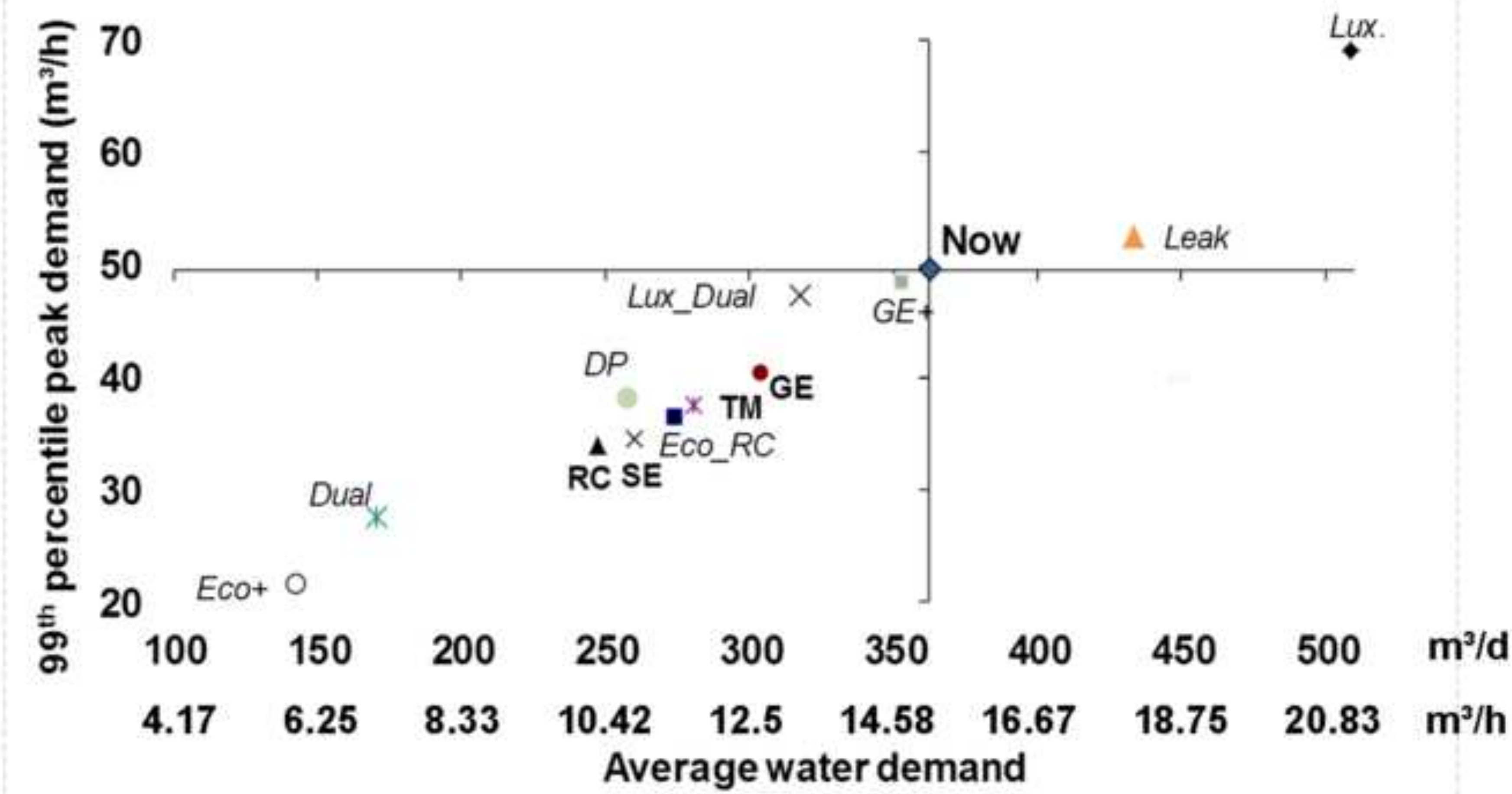
		End-use									Average Total (lcd)	HHS	# HH	ADND (m^3/day)
		BT	BA	DW	KT	OT	SH	WC	WM	LK				
	Now	4.0	4.1	1.7	13.6	23.1	45.9	35.4	14.2	0	142	2.5	1019	362
MS	RC	4.0	2.7	2.6	14.8	2.6	48.3	20.7	12.7	0	108	2.3	1019	253
	SE	4.0	2.7	2.6	15.4	4.6	55.9	20.7	14	0	120	2.2	1019	269
	TM	4.0	2.7	2.6	16.8	17.1	65.9	20.8	13.8	0	144	2	1019	293
	GE	4.0	2.7	2.6	17.2	21.7	69.5	22.4	15.6	0	156	1.9	1019	302
HS	Eco+	4.0	0	0.2	11.7	0	24.9	6.0	0.3	0	47	2.9	1019	139
	Dual	4.0	4.1	1.7	13.6	0	45.9	0	0	0	69	2.5	1019	176
	Eco_RC	4.0	3.1	2.8	11.7	2.6	49.8	6.0	12.2	0	92	2.3	1019	216
	Lux_Dual	4.0	4.1	1.7	13.6	0	102	0	0	0	125	2	1019	255
	DP	4.0	2.7	2.6	17.2	21.7	97.8	22.4	15.6	0	184	2.5	713	328
	GE+	4.0	2.7	2.6	17.2	21.7	97.8	22.4	15.6	0	184	2	1019	375
	Leak	4.0	4.1	1.7	13.6	23.1	45.9	35.4	14.2	28.4	170	2.5	1019	433
	Lux.	4.0	4.1	1.7	13.6	23.1	102	35.4	14.2	0	198	2.5	1019	504

Note: MS: medium stress, HS: High stress, BT: Bath room tap, BA: Bath, DW: dishwasher, KT: kitchen tap, OT: outside tap, SH: shower, WC: toilet flushing, WM: Washing machine, LK: leak, HHS: household size (Inhabitants), HH: household, ADND: average daily network demand. Lux.: luxury, GE: global economies; RC: Regional communities, SE: Strong Europe and TM: Transatlantic Markets, DP: Diminishing population

List of figures

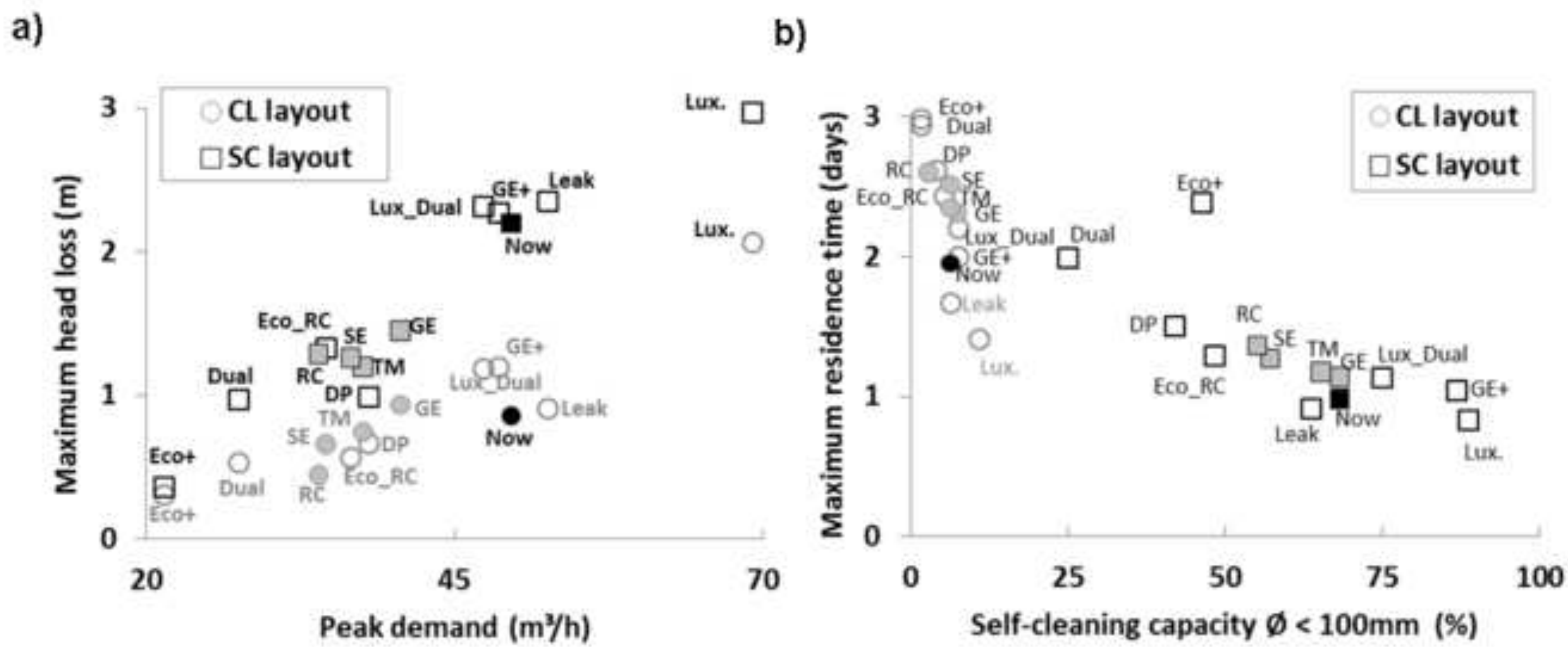

1. Define (three) criteria and (four) indicators to evaluate performance
2. Define drinking water demand scenarios with representatives of (Dutch) water companies
3. Select (two) network(s)
4. Simulate (30) daily patterns (per connection with end-use model SIMDEUM)
5. Run a hydraulic model for each scenario and for each pattern (3-day simulation with EPANET)
6. Determine the variation range of the criteria with relation to a reference value (current situation)
7. Discuss the results with the representatives and consider the results during the planning of pipe replacement, pumping regime and maintenance activities.

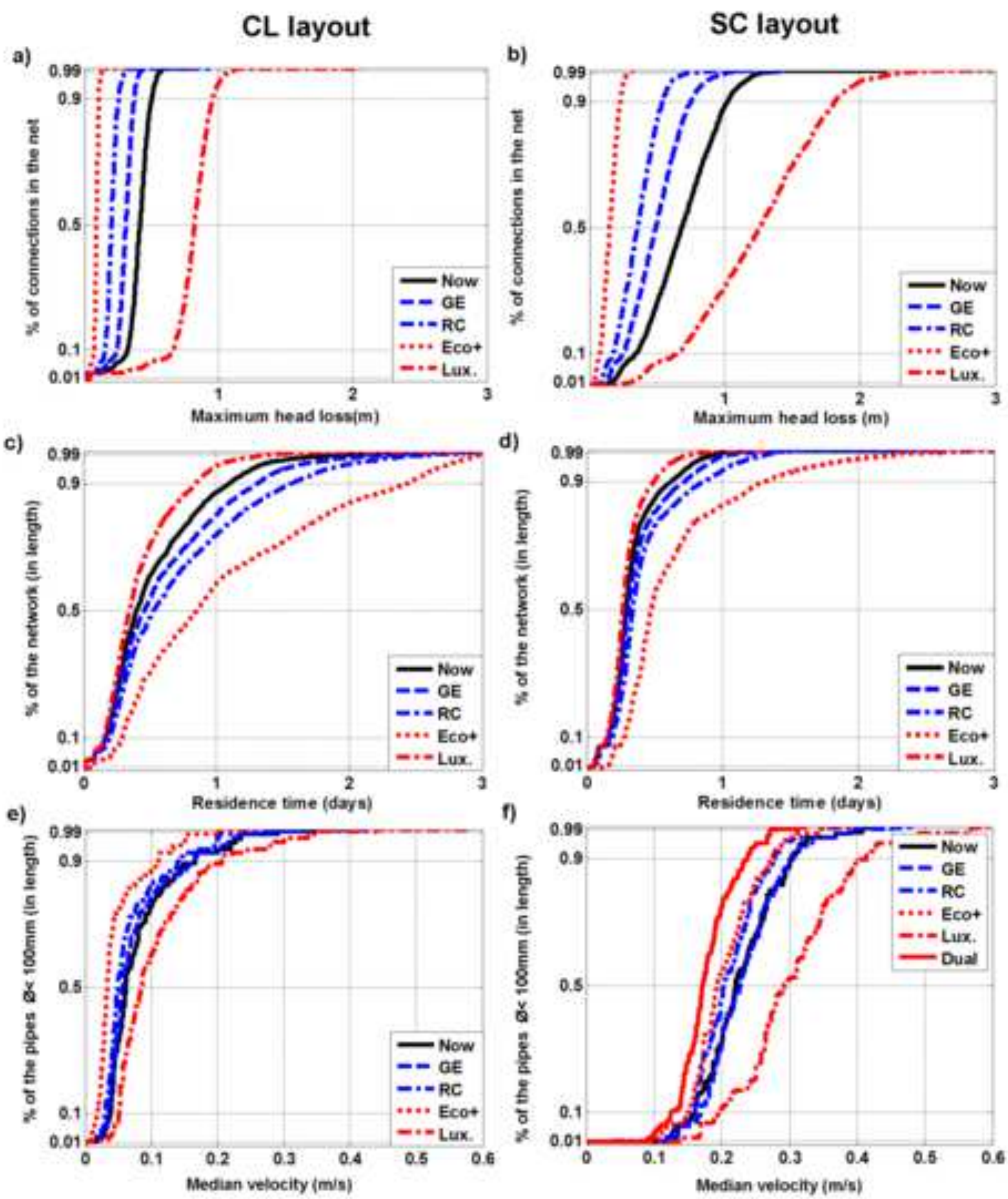

a)
Transport network: 100 m head
Node elevation: 53 m
Pipe diameters:
ϕ < 100 mm
ϕ ≥ 100 mm
Scale:
100
Node elevation: 65 m
b)
Transport network: 100 m head
Node elevation: 53 m
Pipe diameters:
ϕ < 100 mm
ϕ ≥ 100 mm
Scale:
100m
Node elevation: 65 m

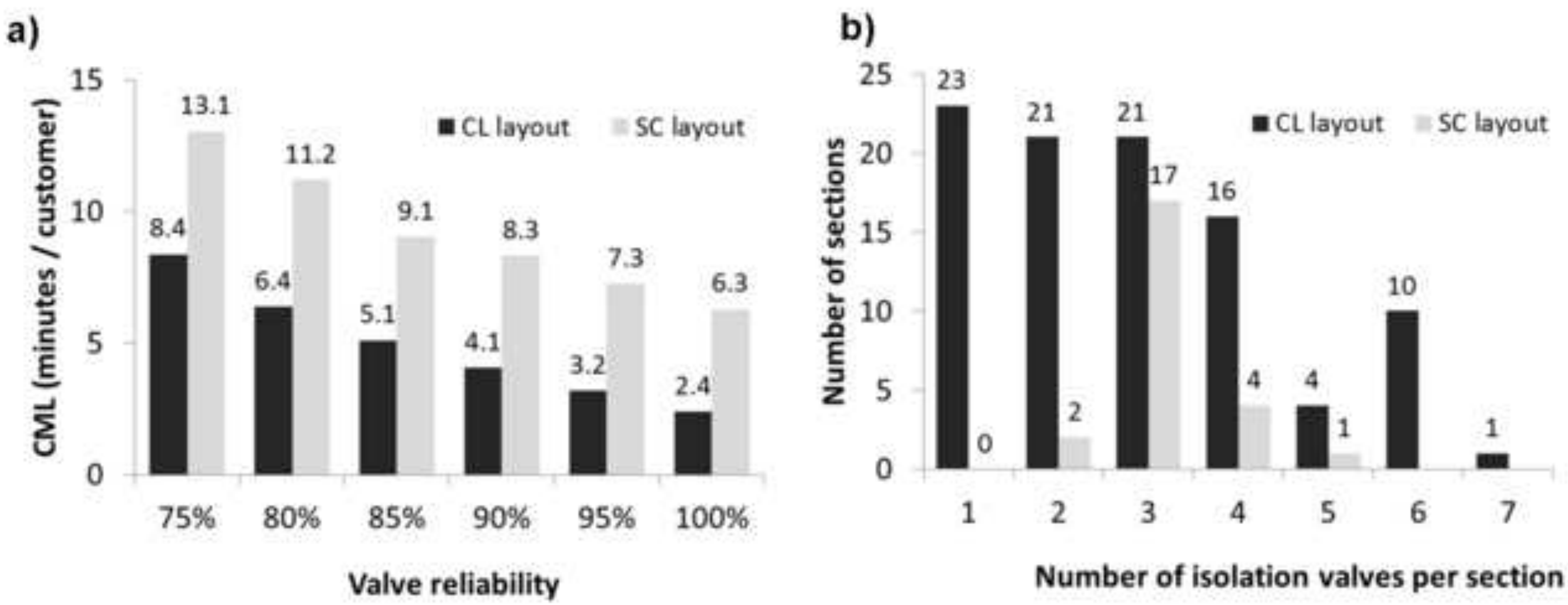

99th percentile peak demand (m³/h)
70
60
50
40
30
20
Lux.
Now
Leak
Lux_Dual
GE+
DP
GE
TM
Eco_RC
RC SE
Dual
Eco+
100
150
200
250
300
350
400
450
500
m³/d
4.17
6.25
8.33
10.42
12.5
14.58
16.67
18.75
20.83
m³/h
Average water demand

Figure

Click here to download Figure Fig 4.tif




CL layout
SC layout
a)
b)
c)
d)
e)
f)
% of connections in the net
Maximum head loss(m)
Maximum head loss (m)
% of the network (in length)
Residence time (days)
% of the pipes Ø< 100mm (in length)
Median velocity (m/s)
Now
GE
RC
Eco+
Lux.
Dual
0.99
0.9
0.5
0.1
0.01


a)
CML (minutes / customer)
15
10
5
0
CL layout
SC layout
8.4
13.1
6.4
11.2
5.1
9.1
4.1
8.3
3.2
7.3
2.4
6.3
75%
80%
85%
90%
95%
100%
Valve reliability
b)
Number of sections
25
20
15
10
5
0
CL layout
SC layout
23
0
21
2
21
17
16
4
4
1
10
1
1
2
3
4
5
6
7
Number of isolation valves per section

Figure

Click here to download Figure Fig 7.tif