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Report on Flushing Planning Algorithm testing on the flushing zones of the drinking water distribution system of the city of Amsterdam

Horizon 2020 Marie Skłodowska-Curie Research and Innovation Staff Exchange project WAT-QUAL

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DISCLAIMER

The findings, interpretations, and conclusions expressed herein are those of the authors.

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1. Introduction

The subject of this report is the presentation and analysis of the flushing plans, and the overall performance of the newly developed Flushing Planning Algorithm (FPA). FPA was used to derive flushing plans for five (four new + test) different flushing zones in the city of Amsterdam. Flushing plans were derived under the scope of the secondments, organized within H2020 MSCA WatQual project, during which Damjan Ivetić and Željko Vasilić were seconded to the public water utility Waternet. In order to optimize the efficiency and the cost of the flushing procedures, conducted by the water utilities, and automize the design of the flushing plans the FPA algorithm was developed. The FPA is using the graph-theory algorithms, modified to account for the specific topological, geometrical, and hydraulic characteristics of the water distribution networks, for the design of the flushing plans.

Flushing of the drinking water distribution systems is conducted after a certain flushing zone is identified to have a high risk of discoloration. Typically, flushing planning is performed manually and can be, and usually is time-consuming. To derive a flushing plan for a flushing zone, a set of sequential flushing operations needs to be defined, in which the secondary and tertiary network pipes, meeting multiple criterion, will be flushed. For each flushing operation a set of valves manipulations is needed to converge the water flow, from a clearwater front, through the pipes that are set to be flushed, and out of the system via output hydrant. Clearwater fronts are identified with in-situ turbidity measurements. To perform the pipe flushing, the water flow used to flush a pipe, needs to meet a set of hydraulic criteria, in order to allow for the discoloration to be appropriately addressed and removed. From the business perspective, the flushing plan should be economical in terms of the minimal expenditure of the time and resources (e.g. drinking water) for the implementation. Here, a possibility for the automatization of the flushing planning with the newly developed FPA algorithm, was tested and analyzed. The FPA algorithm was designed to address the flushing planning by taking into the account all the above-mentioned criteria.

FPA was used to derive the flushing plans for four flushing zones of the Amsterdam water distribution network which are currently prioritized for the flushing, due to the high discoloration risk. The resulting flushing plans are presented here in detail. Performance of the FPA, in terms of the cost and efficiency optimization, was validated against the existing manually derived flushing plans for one test flushing zone. Several performance indicators (PI) were used for the comparison: effective flushing duration, number of valve manipulations, water expenditure and estimated cost. The results show that the FPA can reduce the overall cost of the flushing procedures, in terms of time and resource expenditure. Furthermore, by using physical/hydraulic based rules and constraints, the control of the efficiency and effectiveness of the flushing is significantly improved.

2. Methodology

The Flushing Planning Algorithm (FPA) version, used in this report, is developed in the MATLAB programming environment. Currently, *inputs* for the FPA are the text (.inp) EPANET network models of the flushing zones. Results of the FPA (*outputs*) are the graphical schemes of the derived flushing plans, including each flushing operation with relevant data representation. Additionally, EPANET codes of the governing network elements for each flushing operation can be generated.

In the first step the FPA uses the network data to define the *flushable parts* of the flushing zone (or flushing subzones), meeting certain Geometrical criterion (2.1. Geometrical criteria). Flushable parts of a single flushing zone are usually made of several flushing subzones, which are separated by larger non-flushable pipes.

Next, within the flushable parts of the network, the *flushing segments* are derived. Each flushing segment is defined as the shortest, unique path of the network pipes, connecting a clearwater front and a hydrant (brandkraan), or two hydrants.

Flushing segments can be identified as the building blocks for *flushing operations*. The flushing operations are defined using the graph-theory propagating algorithms, modified to account for specific topological, geometrical and hydraulic rules and constraints. To form each flushing operation, a set of flushing segments need to be combined to form a path, between an input clearwater front and an output hydrant, in such manner that a set of Hydraulic criteria (2.2. Hydraulic criteria) are satisfied. Clearwater fronts are initially defined as nodes where the flushable parts are connected to the pipes of larger diameter, but can include also the nodes which were already flushed within the specific flushing plan. For each flushing operation, a set of valves need to be manipulated (closed or possibly opened), in order to converge the water flow through the flushed pipes. To support appropriate valve manipulations identification, isolation segments are identified as the segments of the network that can be isolated from the rest, using a certain set of valves.

A union of specific flushing operations, covering all of the flushable parts of the flushing zone, defines a *flushing plan*. Clearly a large set of possible combinations of various flushing operations, or flushing plans can be defined for a certain flushing zone. Here, the objective was to minimize the costs of the flushing, thus satisfying appropriate Economic criteria (2.3. Economic criteria).

In this report, the flushing plans derived with FPA are graphically represented as unions of the flushing operations. The resulting flushing plan visualization is elaborated in section 2.4.

Finally, it should be stated that a more detailed description of the FPA underlying methodology will be published in the appropriate scientific journal paper and/or proceedings of the appropriate conference.

2.1. Geometrical criteria – Flushable parts

Good management practice, used in the Waternet and Netherlands in general, states that only parts of the secondary and tertiary potable water distribution network should be flushed within the active measures employed to address the discoloration issues. More precisely, within each flushing zone only pipes satisfying following criteria are identified as flushable parts:

- $Pipe\ Diameter \geq 50\ mm$
- $Pipe\ Diameter \leq 150\ mm$

Seldom, pipes not satisfying the above state criteria can be manually included in the flushable parts, if topologically they are amid the flushed network.

Typically, flushable parts of a single flushing zone are divided into several flushing subzones. Each subzone is separated from the rest of the flushable parts by larger non flushable, feeding pipes.

2.2. Hydraulic criteria – Flushing operation

The water flow used for the flushing, must be directed from the clearwater front (CWF). Typically, turbidity measurements are used to define the clearwater front in the network. Here, initially the CWF nodes in the flushable parts are defined as nodes where these parts of the network are connected to the larger non-flushable pipes. As the flushing operations, within the flushing plan, are sequentially conducted, CWF is propagating within the network.

To perform a successful flushing of the network pipe, the water flow should induce critical shear stress on the pipe walls, needed to start the motion of the settled particles. The value of the induced shear stress is directly proportional to the square of the mean flow velocity.

Good management practice, used in the Waternet, states that mean flow velocity in the flushed pipes should satisfy:

- $V \geq 1.5\ m/s$

This condition was used in the FPA here, although in the next versions a shear-stress based approach should be considered.

Furthermore, the duration of the flushing should be such that:

- MIN of three water volume turnovers is achieved in the pipes

The duration for a single volume turnover corresponds to the time needed for water to travel through all the pipes included in the flushing operation. With the increase of the length of the pipes within each of the flushing operations, the duration of the flushing increases. The velocity in each pipe is calculated based on the minimum flushing flow rate Q_{min}, and pipe diameter. Flow rate Q_{min} is defined for each flushing operation based on the biggest pipe diameter and velocity criterion. Thus, If the velocity criterion is satisfied in the pipe with the largest diameter, in the smaller pipes of the flushing operation, the velocities will be higher.

When defining the maximum length of the pipes within the flushing operations, it should be noted that this value is essentially governed with the available pressure head and the roughness of the pipes. The rationale is that a sufficient pressure drop is needed, between the clearwater front and the output hydrant, to allow for the $V \geq 1.5\ m/s$ to be achieved throughout the flushed pipes. In the Waternet a practical constraint is used for manually derived flushing operations:

- Length of the Flushing operation $\leq$ 300 m.

Within the FPA, a more accurate, hydraulically based constraint is used instead, stating that the pressure drop for each flushing operation should:

- $\text{Pressure drop } \leq 1.6$ bar
- $\text{Pressure drop} = \text{ Pressure drop}(\text{Q}_{min})$

A pressure drop maximum value is determined based on the minimal available pressure assumption stating that for each of the start nodes for the flushing operation, a pressure head of min 2.0 bar is available. A pressure drop is calculated for each pipe, based on the pipe roughness value, pipe diameter and the minimal flowrate Q_{min} needed to satisfy the $V \geq 1.5\ m/s$ in all the pipes, within a single flushing operation. Here, the pipe roughness was determined in the drinking water distribution network model calibration procedure, prior to the application of the FPA algorithm, and were available in the EPANET model. Alternatively, the roughness can be estimated (modelled) using the pipe material, current condition and age data.

2.3. Economic criteria – Flushing plan

The FPA algorithm can derive multiple flushing plans for each flushing zone. In general, it uses every initial clearwater front node in the flushing zone as a starting node for the propagation and flushing plan derivation. For each of the derived flushing plan, flushing costs are estimated. Here, the flushing costs are estimated based on the time needed for the implementation of the flushing plans and amount of drinking water being spent on the actual flushing. Computation of the flushing costs is based on the following assumptions:

- $Flushing\ is\ performed\ by\ 2\ technicians\ (no\ of\ Technicians)$

- $Technician\ man\ hour = 60$ €

- $Cost\ of\ water = 1.54$ €/m^3

- $Flushing\ operation\ setup\ time\ = 900\ s = 15\ min$

- $Valve\ manipulation\ time = 450\ s = 7.5\ min$

- $Total\ Flushing\ operation\ time = Flushing\ operation\ setup\ time + no\ of\ Valve\ manipulations * \ Valve\ manipulation\ time + Flushing\ duration$

(Note: Each opening or closing of a Valve is counted as a valve manipulation)

- $Total\ Flushing\ plan\ time = no\ of\ Flushing\ operations * Total\ Flushing\ operation\ time$

To compute $\boldsymbol{Total\ Flushing\ plan\ cost,}$ water expenditure (ΔV) must be calculated, based on the flushing durations and minimal flushing flowrate Q_{min}. Once ΔV is computed, cost of a flushing plan implementation is defined as:

- $\boldsymbol{Total\ Flushing\ plan\ cost} = Total\ Flushing\ plan\ time * no\ of\ Technicians * Technician\ man\ hour + \Delta V * Cost\ of\ water$

Each Flushing plan, for a certain input clearwater front, is designed to minimize the Total Flushing plan costs. Primarily, the objective was to minimize the number of flushing operations, number of valve manipulations, flushing durations and water expenditure. Additionally, the flushing operations are ordered in a such manner that the valve manipulations (using the same set of valves for more flushing operations) and the distance traveled by technicians are minimized. Once the Flushing plans, for a certain flushing zone, were derived, one optimal flushing plan for a certain flushable zone is defined and presented.

2.4. Result visualization

The derived flushing plans are represented through a series of flushing operations schemes. An example flushing operation scheme is presented in Figure 1. Each flushing operations is defined with the source CWF (FO CWF), a node on the larger diameter pipes, from which a clearwater front can be provided for the flushing. Furthermore, a start node (FO Start) is shown, defining a starting point for the pipes that are being flushed, and outlet hydrant (FO Outlet) where the flushing box with the flow, pressure and turbidity measuring equipment will be installed. The pipes in current flushing operation are shown in light green color, while the previously flushed pipes (in current flushing plan) in cyan.

Within each of the presented flushing operations, as parts of the flushing plans, a set of relevant data is also presented (Figure 1). This data is computed within the FPA, and is used throughout the algorithm for the both the derivation of the flushing plans, optimization and finally the implementation. Here, the relevance of the data is briefly explained:

- **Flow rate Q_{min} –** A minimal flow rate needed for the flushing of the selected pipes within the presented flushing operation. This value is governed by the largest pipe diameter within the flushing operation and the hydraulic velocity criterion $V \geq 1.5\ m/s$. During the actual flushing of the pipes, technicians performing the flushing operation should verify that this value is achieved at the outlet hydrant (with EM flowmeter installed in the flushing box), in order to meet the velocity criteria.
- **Estimated cost –** A cost estimate for the implementation of the presented flushing operation. This value is computed based on the Economic criteria defined in section 2.3.
- **Flushed length –** A total length of the pipes being flushed in the presented flushing operation.
- **Pressure drop –** A total pressure drop along the flushed pipes, governed by Q_{min}, Diameter, Length and Roughness of the pipes.
- **Num of valves –** A total number of valves that should be closed to converge the water flow through the flushed pipes. These valves are represented with red and blue triangles. Red triangles correspond to the valves that are closed for the presented flushing operation. Blue triangles correspond to the valves that were closed for previous flushing operation and should remain closed.

- **Flushing duration –** Effective duration of the flushing of the pipes. This value is governed by the length of the pipes and the three volume turnovers criterion.
- **Volume of water –** A total drinking water expenditure for the current flushing operation, expressed in cubic meters.

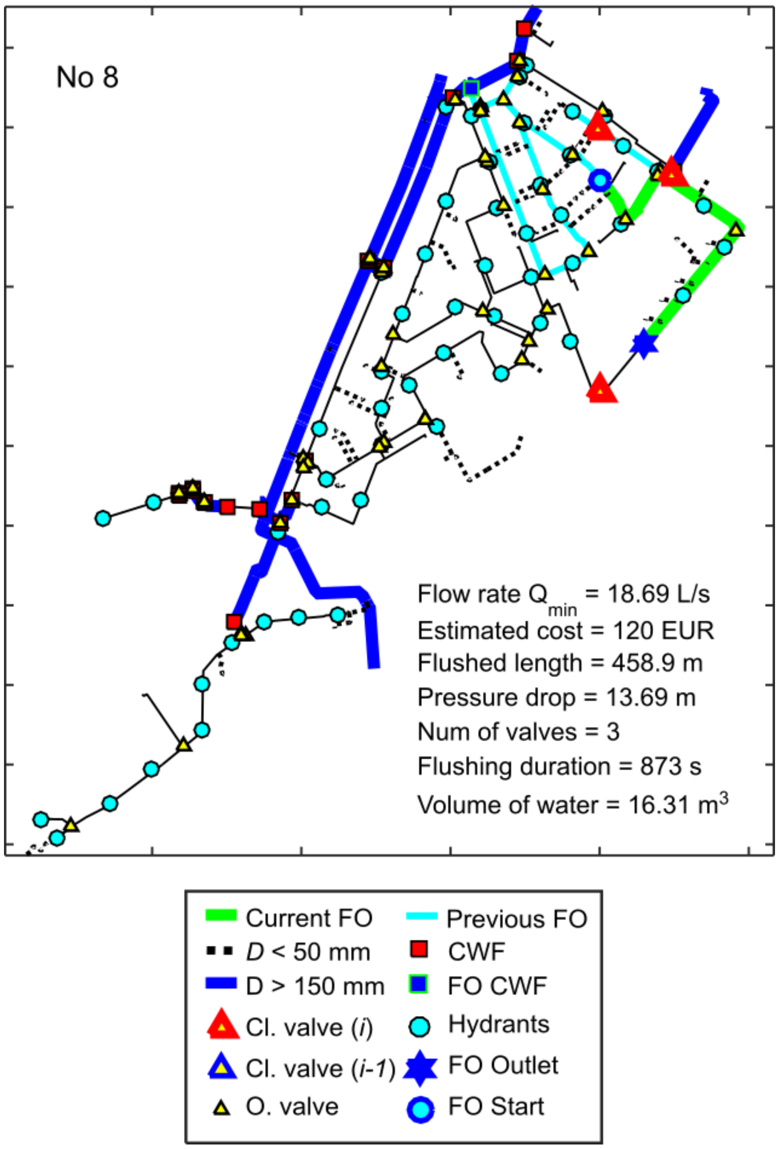

Figure 1 FPA: An example of the graphical representation of the flushing operation

3. Analyzed flushing zones

Five flushing zones of the Amsterdam water distribution system, managed by Waternet, have been analyzed in this report. FPA was applied to derive flushing plans for all of the zones. Four of the zones are currently identified with high discoloration risk. Flushing plans have not been previously designed for these zones. The basic data for these zones is presented in Section 3.1. Furthermore one flushing zone, with existing flushing plan, was used for the validation of the FPA performance. The basic data of the validation zone is presented in Section 3.2.

Using the 3Dnet software (University of Belgrade, Faculty of Civil Engineering) and existing EPANET model of the network, topological, geometrical and hydraulic properties of the flushing zones were extracted and used as input data for the Flushing Planning Algorithm (FPA). For each of the zones, a graphical representation of the FPA flushing segments and isolation segments are also presented here.

3.1. High discoloration risk flushing zones

For the purpose of the FPA performance presentation, Gerrit van Vliet and Ralf de Groot from Waternet, have chosen a set of flushing zones which are currently prioritized for the flushing, due to the high discoloration risk. Four flushing zones were identified in the Mapkit GIS model of the potable water distribution system of the city of Amsterdam.

3.1.1. Zone 1 - Sleutelbloemstraat 34

Zone 1 - Sleutelbloemstraat 34 is located in the Amsterdam Noord. A screenshot from Mapkit software of the Zone 1 is presented in Figure 2.

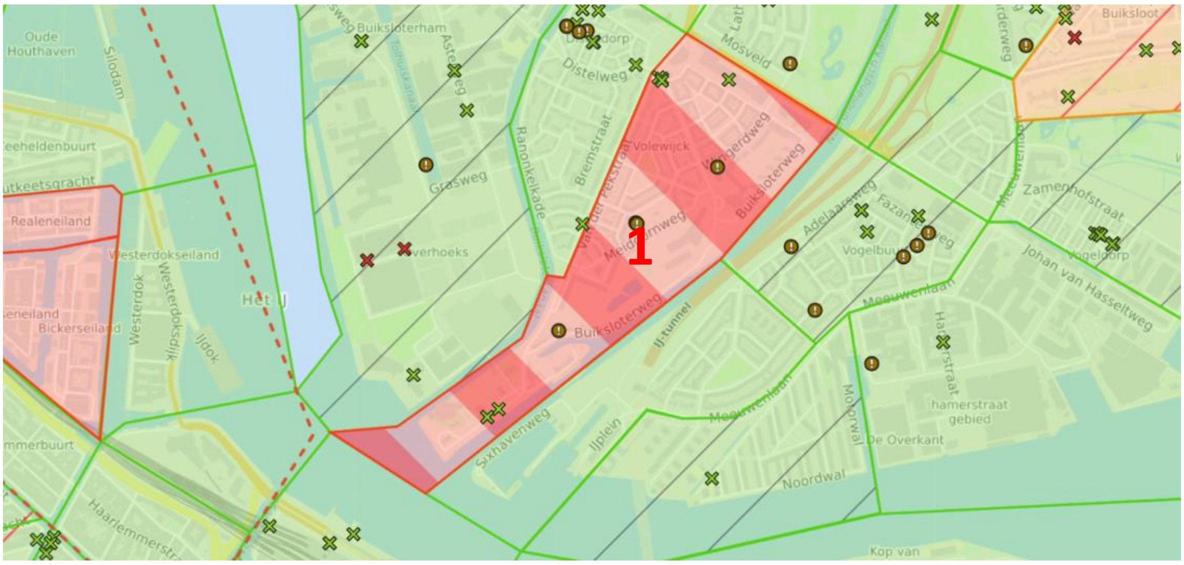

Figure 2 Graphical representation of Flushing Zone 1 - Sleutelbloemstraat 34 within the Mapkit software

FPA flushing segments, and isolation segments, identification result are shown in Figure 3. It can be noticed that the Flushable parts of this zone are separated in three flushable subzones. To the north is the smallest one with two CWF input nodes, in the middle is the biggest zone with five CWF nodes and to the south is the subzone with a single CWF input node.

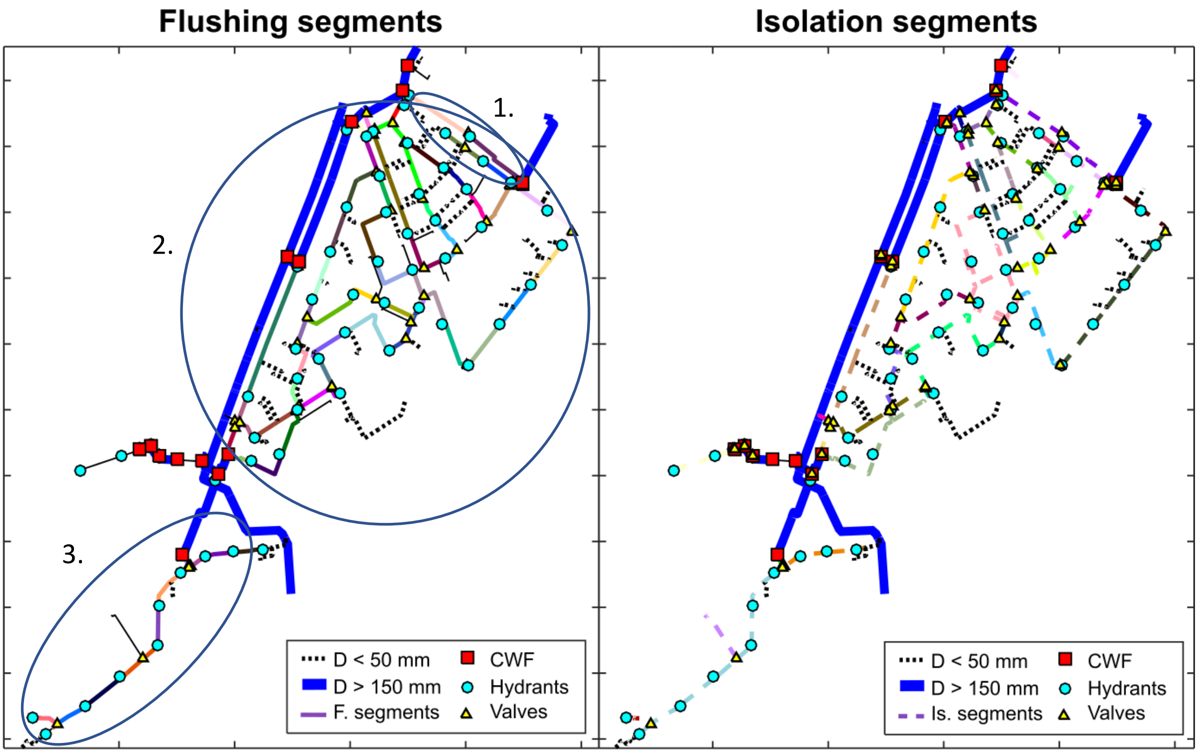

Figure 3 Zone 1 - Sleutelbloemstraat 34, FPA: Left) Identified Flushing segments and flushing subzones; Right) Identified Isolation segments

3.1.2. Zone 2 - Borrendammehof 1 Amsterdam

Zone 2 - Borrendammehof 1 Amsterdam is located in the Amsterdam Nieuw - West. A screenshot from Mapkit software of the Zone 2 is presented in Figure 4.

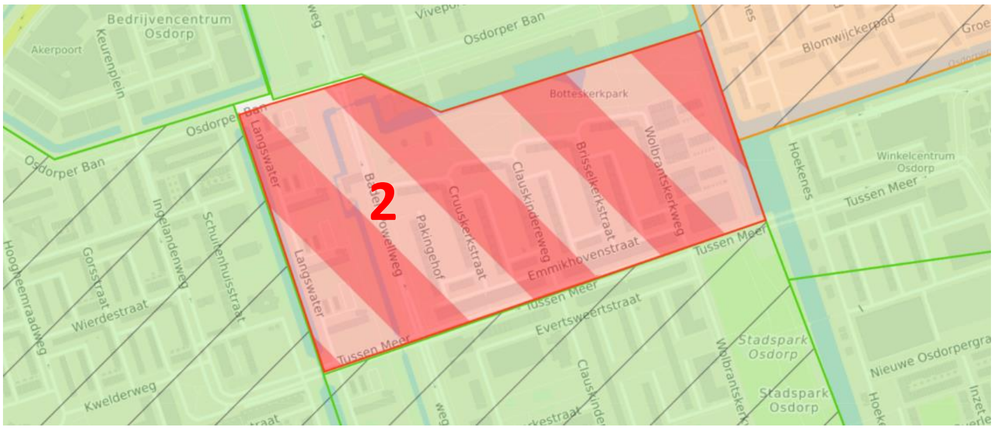

Figure 4 Graphical representation of Flushing Zone 2 - Borrendammehof 1 Amsterdam within the Mapkit software

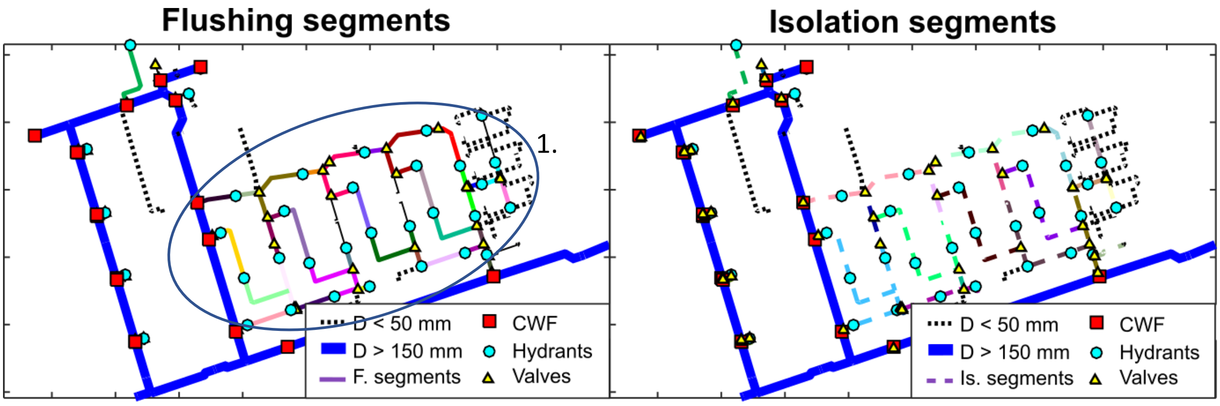

Figure 5 Zone 2 - Borrendammehof 1 Amsterdam, FPA: Left) Identified Flushing segments and flushing subzones; Right) Identified Isolation segments

FPA flushing segments, and isolation segments, identification result are shown in Figure 5. It can be noticed that the Flushable parts of this zone are grouped in a single zone.

However, it was observed that the roughness of the pipes, extracted from the EPANET model for this zone, are relatively high. Due to the fact that the flushing segments can have pipes with various diameters where the minimal flushing flow $\mathbf{Q_{min}}$ is governed by the pipe with the largest diameter in the segment, for over 20% of the identified flushing segments the pressure drop was over > 16 m. Thus, these flushing segments could not satisfy the hydraulic criteria for flushing $V \geq 1.5\ m/s$ necessary for addressing the discoloration issues.

To overcome this issue, flushing plans for Zone 2 were derived in two stages:

1. Firstly, the flushable parts of the network were identified using the following geometric criteria for pipes:

$$128\ mm \leq Pipe\ Diameter \leq 150\ mm$$

   Identified flushing and isolation segments are shown in Figure 6. It can be observed that in the first stage two subzones can be identified.

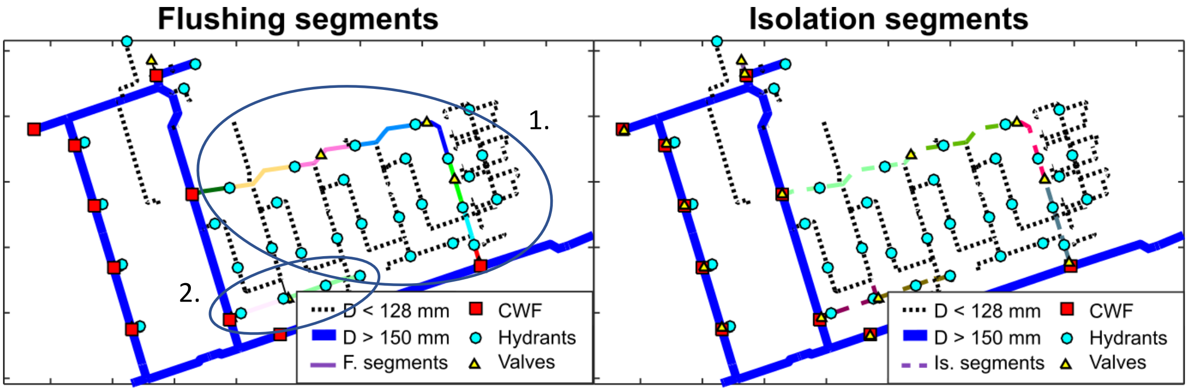

Figure 6 Zone 2 - Borrendammehof 1 Amsterdam for the flushable subzones with 128 mm ≤ D ≤ 150 mm, FPA: Left) Identified Flushing segments and flushing subzones; Right) Identified Isolation segments

2. Secondly, the flushable parts of the network were identified using the following criteria:

$$50\ mm \leq Pipe\ Diameter < 128\ mm$$

Identified flushing and isolation segments are shown in Figure 7. It can be observed that in the second stage two subzones can be identified.

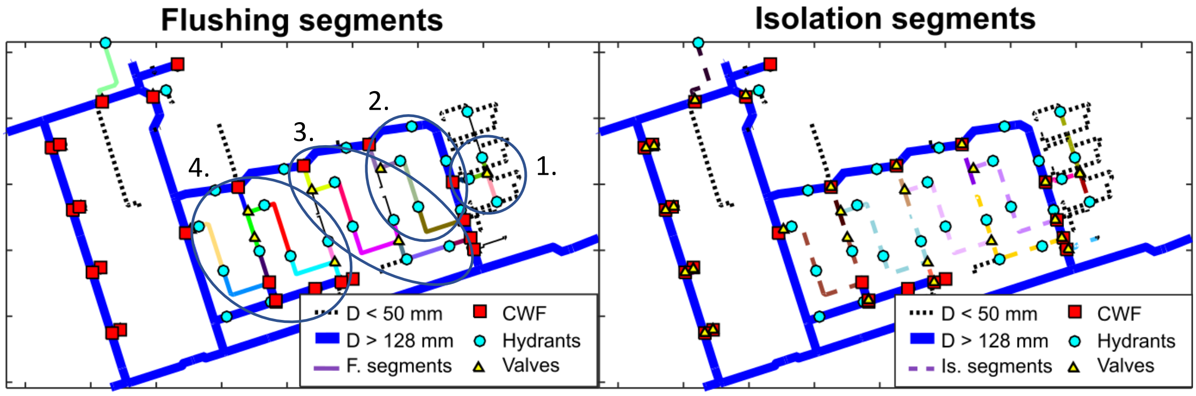

Figure 7 Zone 2 - Borrendammehof 1 Amsterdam for the flushable subzones with 50 mm ≤ D < 128 mm, FPA: Left) Identified Flushing segments and flushing subzones; Right) Identified Isolation segments

3.1.3. Zone 3 - Prof. H. Bavinckstraat 60

Zone 3 - Prof. H. Bavinckstraat 60 is located in the Amsterdam Nieuw - West. A screenshot from Mapkit software of the Zone 3 is presented in Figure 8.

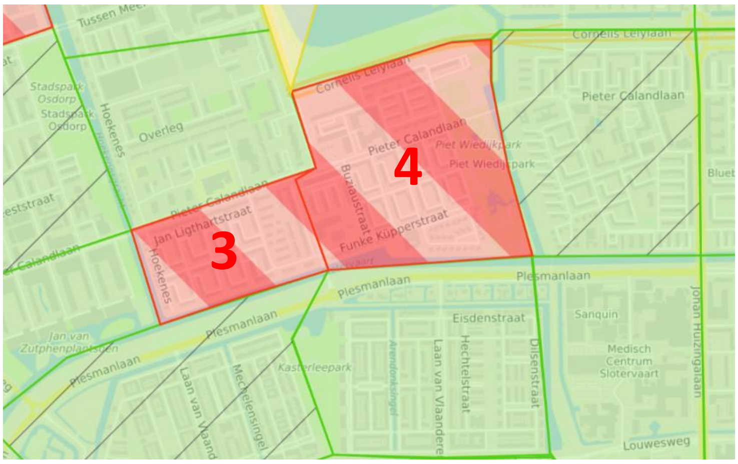

Figure 8 Graphical representation of Flushing Zone 3 - Prof. H. Bavinckstraat 60, and Flushing Zone 4 - Louis Raemaekersstraat 21 within the Mapkit software

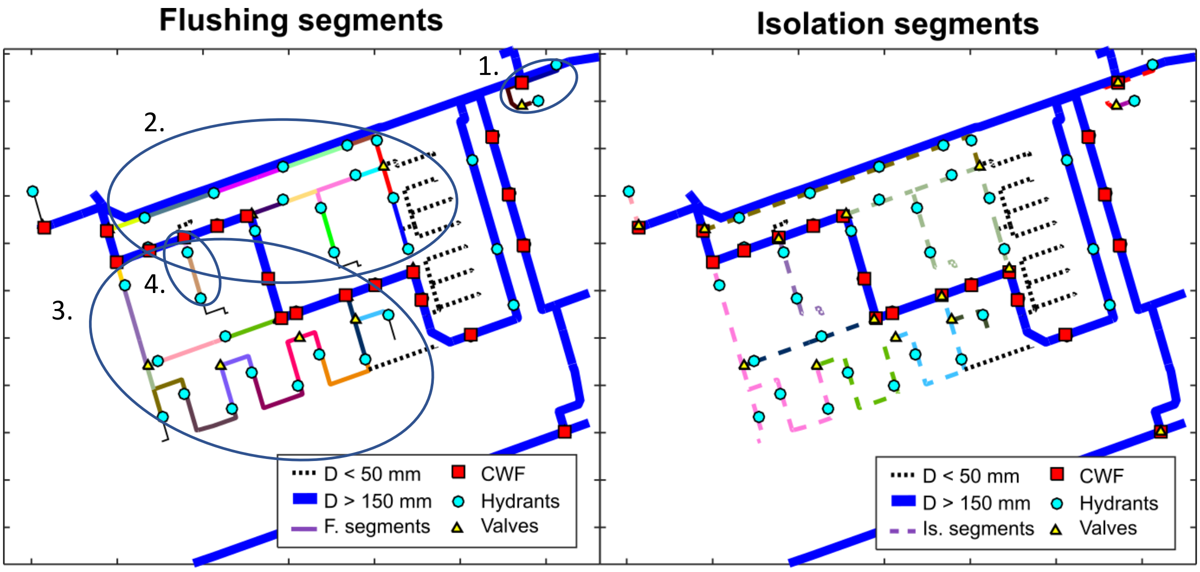

Figure 9 Zone 3 - Prof. H. Bavinckstraat 60, FPA: Left) Identified Flushing segments and flushing subzones; Right) Identified Isolation segments

FPA flushing segments, and isolation segments, identification result are shown in Figure 9. It can be noticed that the Flushable parts of this zone are separated in four (4) flushable subzones. First a small subzone at the northeastern part of the zone with one CWF input node. Next, two subzones make the bulk of the flushable parts of the whole zone, where the second one is located at the north and has three CWF nodes, while the third one is to the south with also three CWF nodes. The fourth subzone is made of a single pipe located in between the second and third flushable subzone.

3.1.4. Zone 4 - Louis Raemaekersstraat 21

Zone 4 - Louis Raemaekersstraat 21 is located in the Amsterdam Nieuw – West, east from the Zone 3. A screenshot from Mapkit software of the Zone 4 is presented in Figure 8.

FPA flushing segments, and isolation segments, identification result are shown in Figure 10. It can be noticed that the Flushable parts of this zone are separated in three (3) flushable subzones. First one is to the northeast with three CWF input nodes, second one to the west with five CWF nodes, and third to the northeast with two CWF nodes.

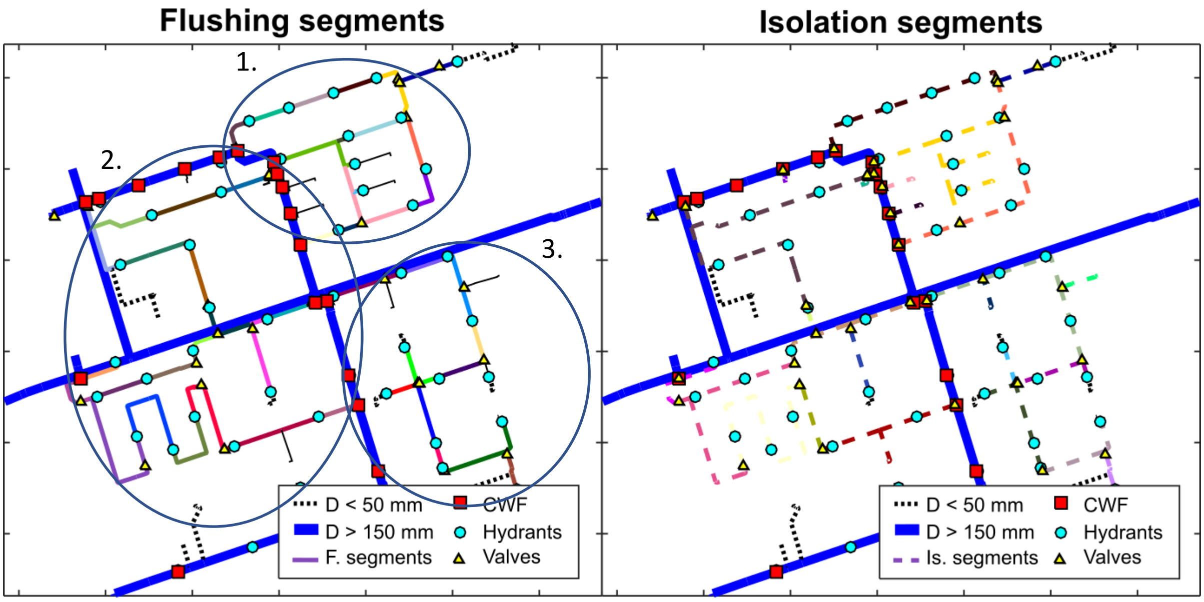

Figure 10 Zone 4 - Louis Raemaekersstraat 21, FPA: Left) Identified Flushing segments; Right) Identified Isolation segments

3.2. Validation (Test) flushing zone - Jan Goeverneurhof 4

Flushing zone Jan Goeverneurhof 4, with existing flushing plan, was chosen for the validation and comparison of the FPA. Flushing plan derived with FPA was compared with the existing, manually derived flushing plan, in order to estimate the cost reduction and efficiency improvement achieved with the FPA.

Validation flushing zone is located in the western part of the Amsterdam. A screenshot from Mapkit software of the validation zone is presented in Figure 11.

FPA flushing segments, and isolation segments, identification result are shown in Figure 10. It can be noticed that the Flushable parts of this zone are separated in four (4) flushable subzones. First one is to the northeast with eight CWF input nodes, second one in the middle with two CWF nodes, third to the west with four CWF nodes, and forth to the southeast with two CWF nodes.

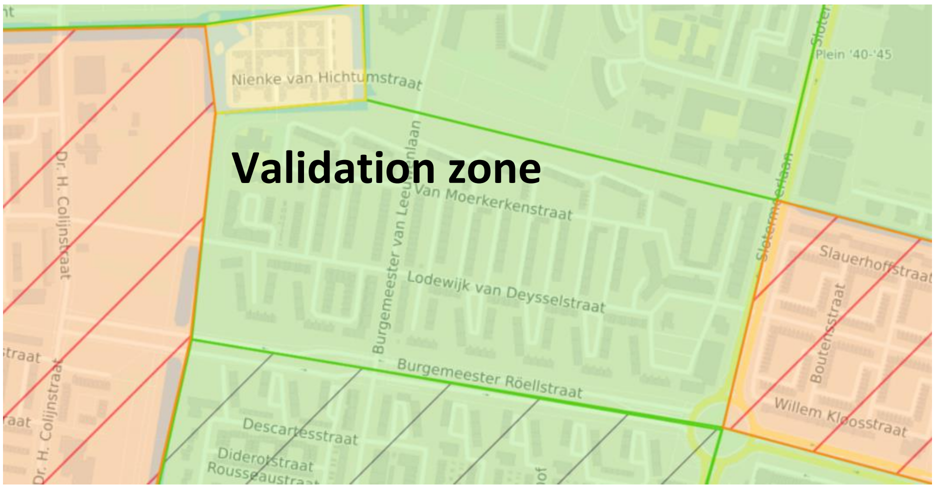

Figure 11 Graphical representation of Validation Flushing Zone - Jan Goeverneurhof 4 within the Mapkit software

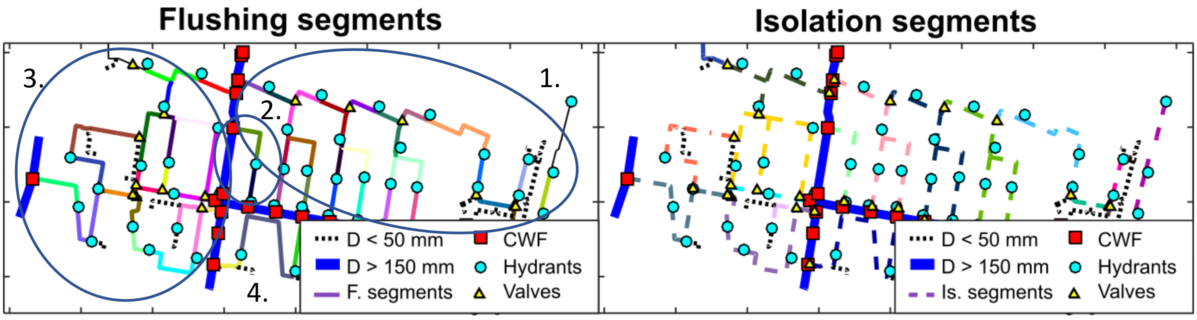

Figure 12 Validation Flushing Zone - Jan Goeverneurhof 4, FPA: Left) Identified Flushing segments; Right) Identified Isolation segments

4. Results

In this section, the flushing plans for the selected flushing zones, derived with the FPA are presented. Flushing zones with high discoloration risk are analyzed in Section 4.1. The resulting flushing plan for the validation zone is shown in section 4.2. and is followed by the performance analysis of the FPA.

For each flushing zone, a direction of propagation for the FPA is defined. Flushing plans for each flushable subzone are presented in the order defined by the direction of the propagation. Additionally, the flushing costs for each subzone, and total cost estimate of the flushing plan implementations are shown.

4.1. Flushing plans for high discoloration risk flushing zones

The resulting flushing plans for the four zones with high discoloration risk are presented in this section.

4.1.1. Zone 1 - Sleutelbloemstraat 34

Using the FPA, flushing plans were derived for each of the available CWF of the three flushable subzones. An optimal combination of the subzone flushing plans is presented here. A North-South direction of the propagation was chosen as optimal for the Zone 1 Flushing plans. Figure 13 shows the flushing operation for the smallest flushable subzone, at the north of the flushing zone. Figures 14 – 18 show the flushing plan for the biggest subzone. Figure 19 shows the flushing plan for the third flushable subzone positioned at the south of the Zone 1. A total cost for the implementation of the flushing plans is estimated to be 2628 € (77 € + 2249 € + 302 €).

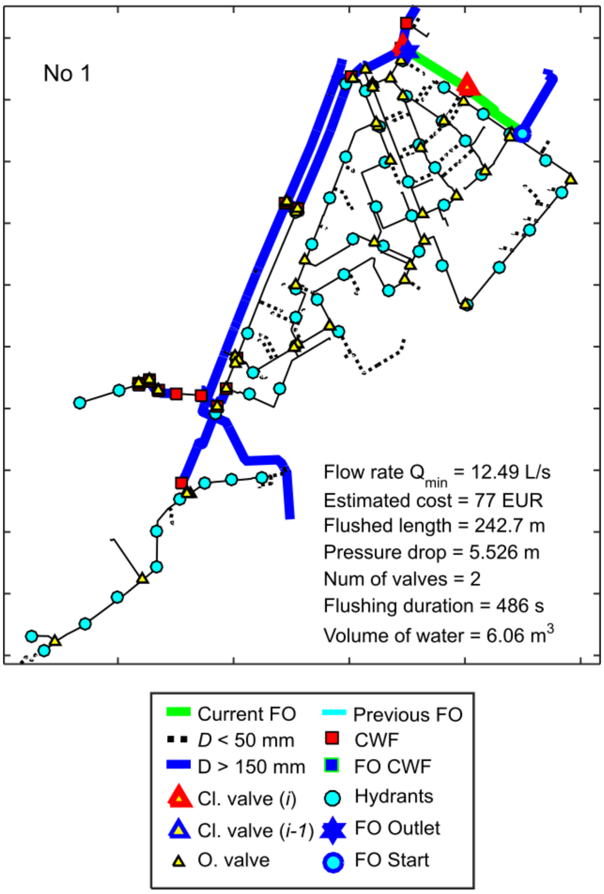

Figure 13 Zone 1 - Sleutelbloemstraat 34, FPA: Flushing operations 1 for the first (smallest) flushable subzone

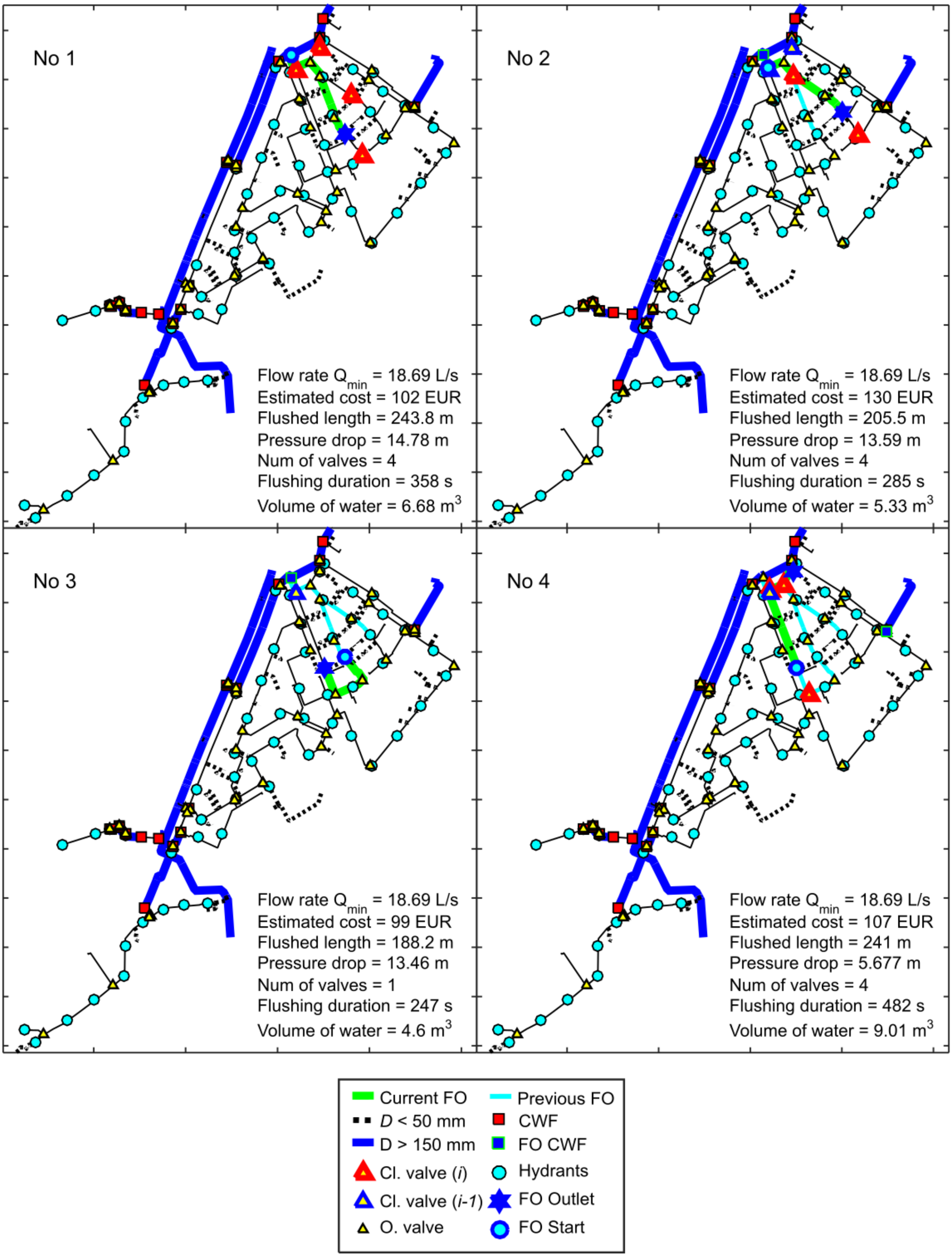

Figure 14 Zone 1 - Sleutelbloemstraat 34, FPA: Flushing operations 1 – 4 for the second (biggest) flushable subzone

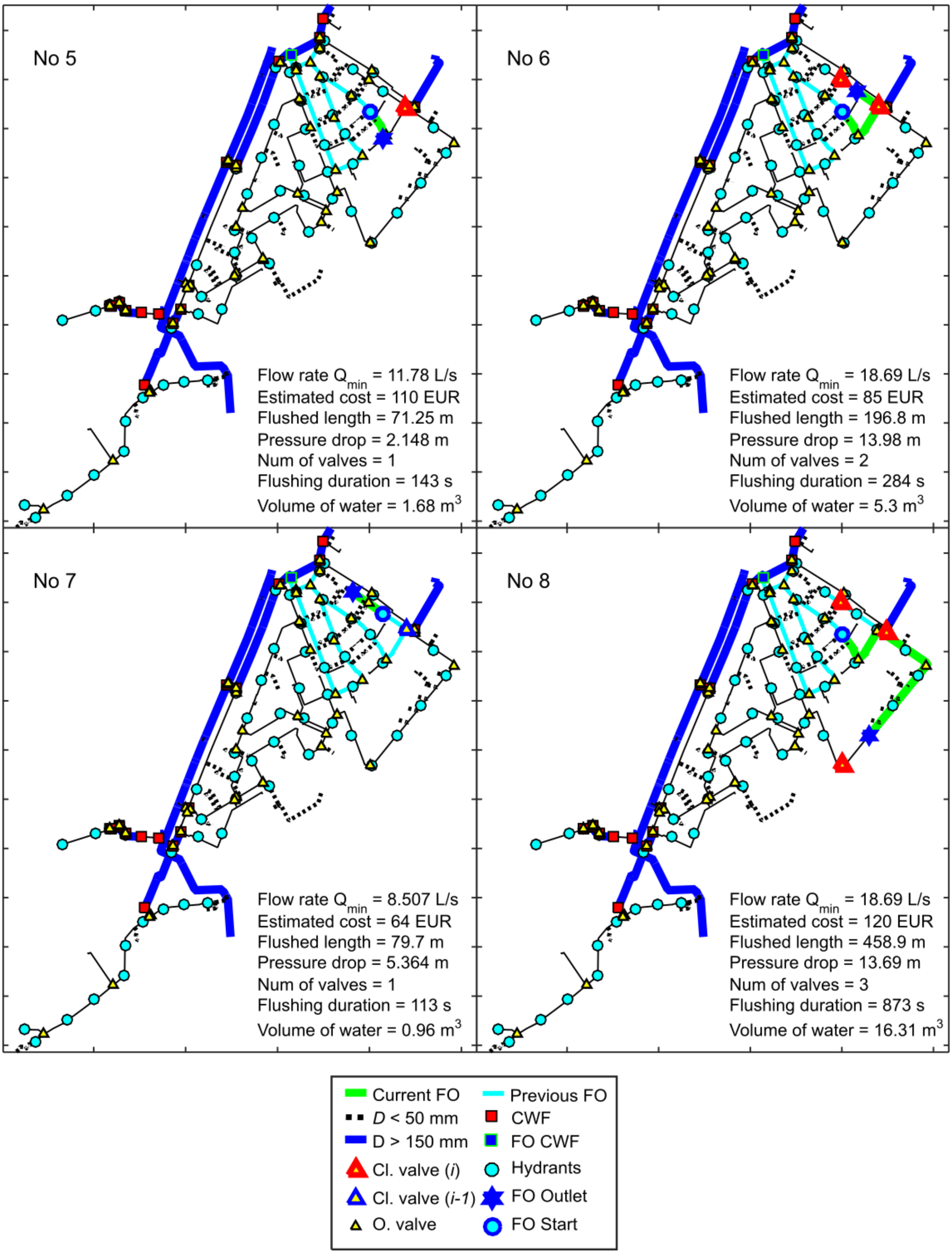

Figure 15 Zone 1 - Sleutelbloemstraat 34, FPA: Flushing operations 5 – 8 for the second (biggest) flushable subzone

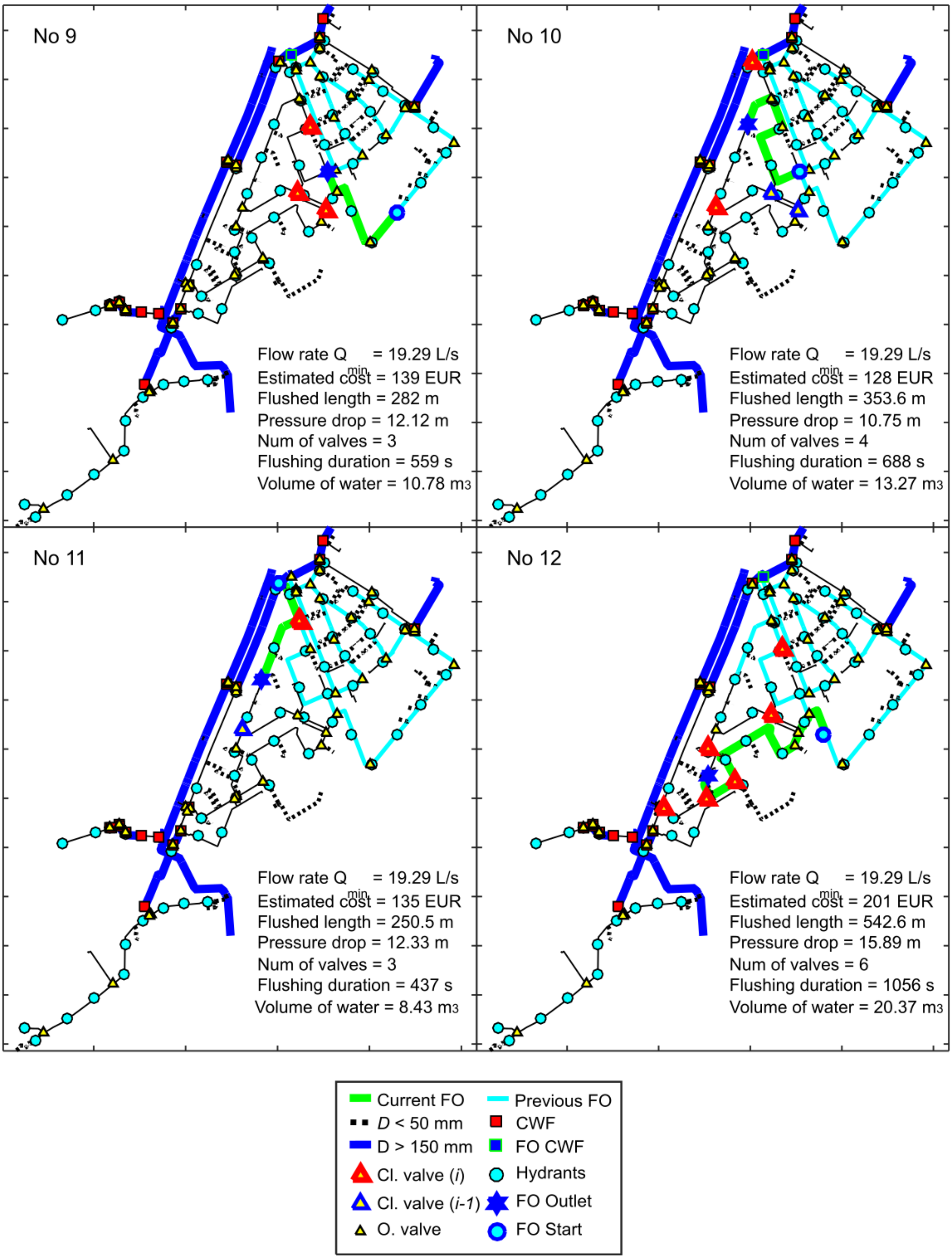

Figure 16 Zone 1 - Sleutelbloemstraat 34, FPA: Flushing operations 9 – 12 for the second (biggest) flushable subzone

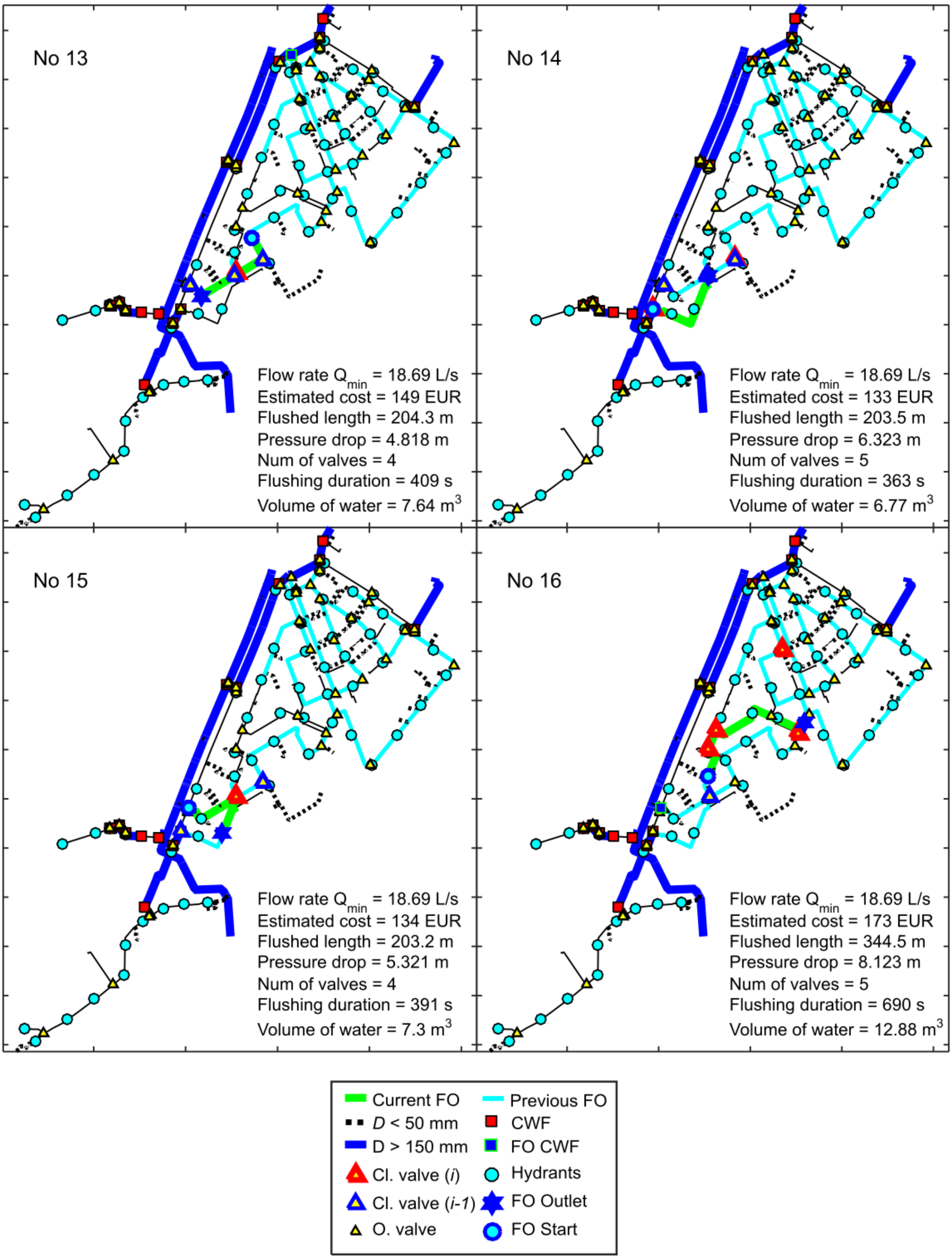

Figure 17 Zone 1 - Sleutelbloemstraat 34, FPA: Flushing operations 13 – 16 for the second (biggest) flushable subzone

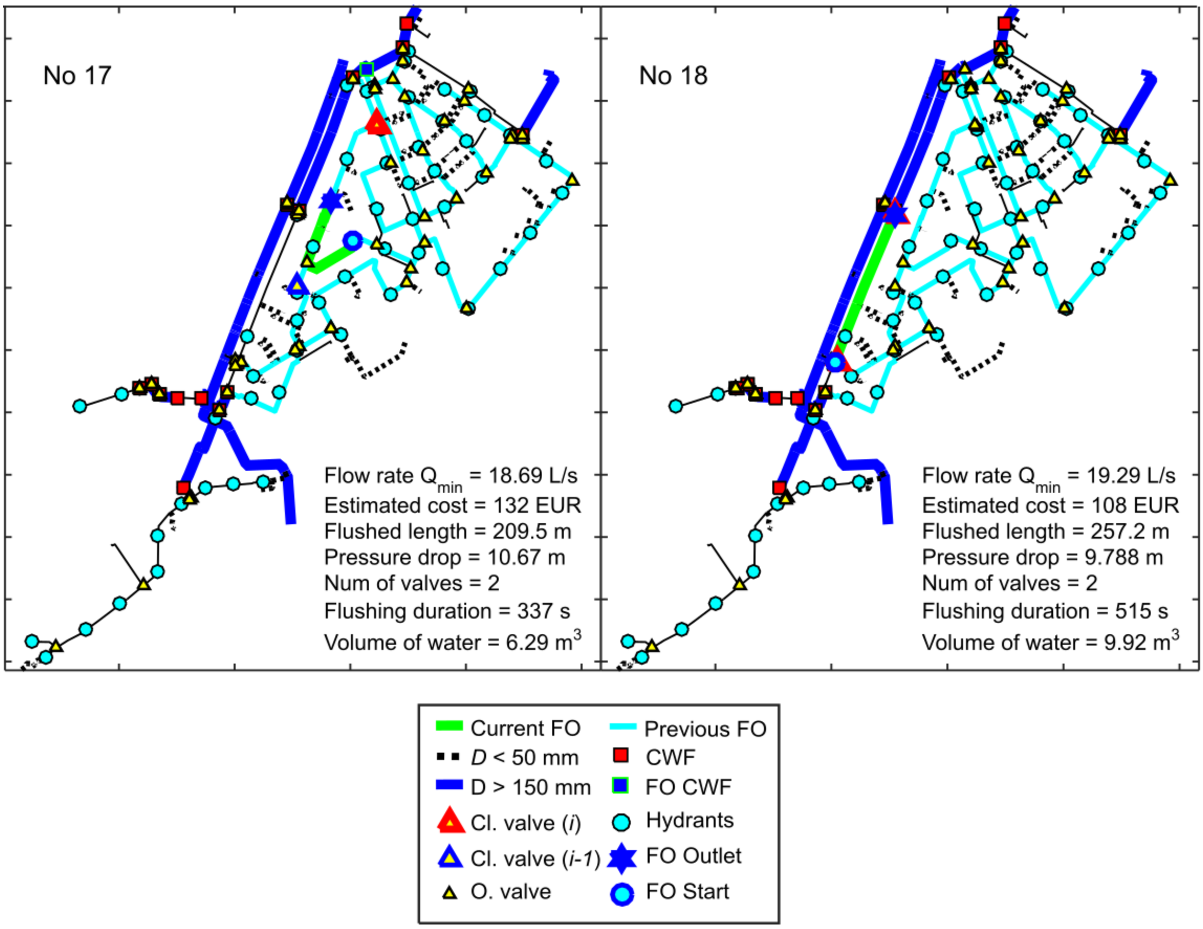

Figure 18 Zone 1 - Sleutelbloemstraat 34, FPA: Flushing operations 17 – 18 for the second (biggest) flushable subzone

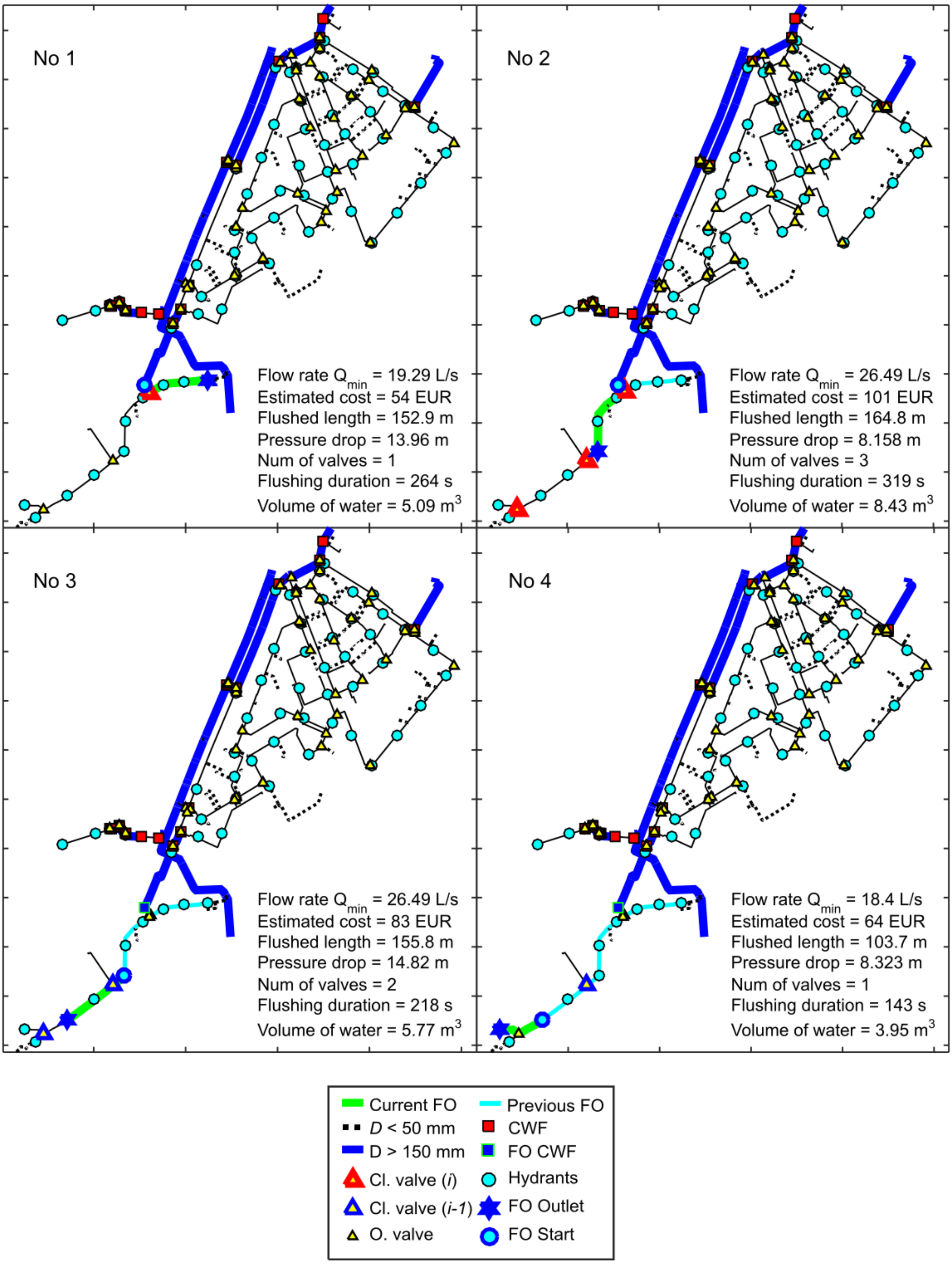

Figure 19 Zone 1 - Sleutelbloemstraat 34, FPA: Flushing operations 1 – 4 for the third flushable subzone

4.1.2. Zone 2 - Borrendammehof 1 Amsterdam

Using the FPA, flushing plans were derived in two stages, where the first stage (128 mm ≤ D ≤ 150 mm) is divided in two subzones, while the second stage (50 mm ≤ D < 128 mm) in 4 subzones. An optimal combination of the subzone flushing plans, for both stages, is presented here. An East-West direction of the propagation was chosen as optimal for the Zone 2 Flushing plans.

First stage (128 mm ≤ D ≤ 150 mm): Figure 20 shows the flushing plan for the eastern flushable subzone. Figure 21 shows the flushing operation, for the second western subzone. A total cost for the implementation of the first zone flushing plans is estimated to be 250 € (185 € + 65 €).

Second stage (50 mm ≤ D < 128 mm): Figure 22 shows the flushing operation for the first flushable subzone, while Figure 23 shows the flushing operation for the second subzone. In Figures 24 and 25 flushing plans for the third and fourth subzone are presented. A total cost for the implementation of the first zone flushing plans is estimated to be 674 € (111 € + 69 € + 231 € + 263 €).

A total cost for the implementation of the flushing plans in the Zone 2 is estimated to be 924 € (250 € + 674 €).

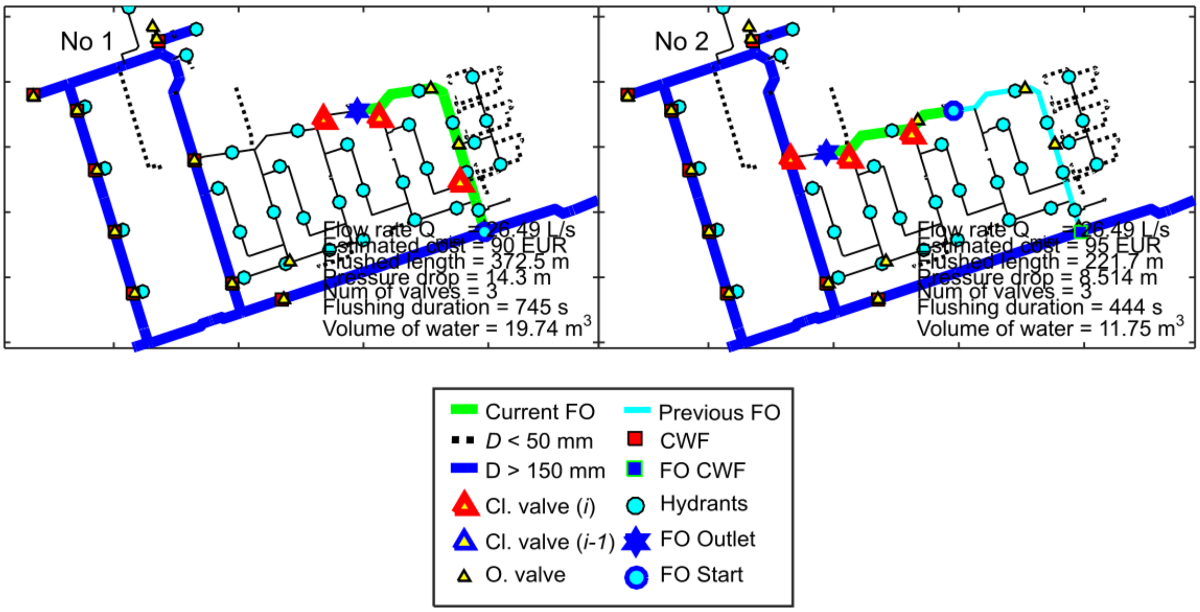

Figure 20 Zone 2 - Borrendammehof 1 Amsterdam (First stage), FPA: Flushing operations 1 – 2 for the first flushable subzone

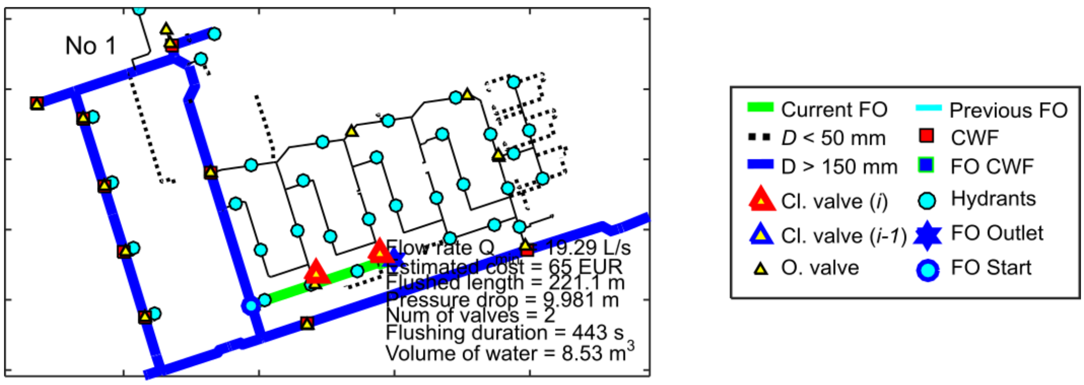

Figure 21 Zone 2 - Borrendammehof 1 Amsterdam (First stage), FPA: Flushing operation 1 for the second flushable subzone

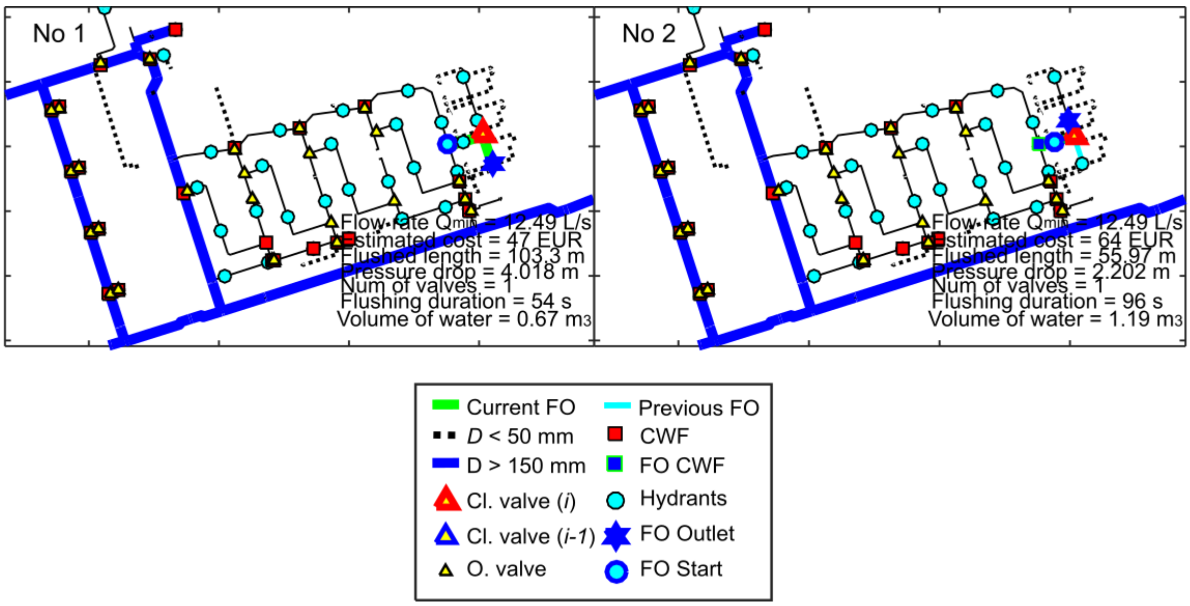

Figure 22 Zone 2 - Borrendammehof 1 Amsterdam (Second stage), FPA: Flushing operations 1 - 2 for the first flushable subzone

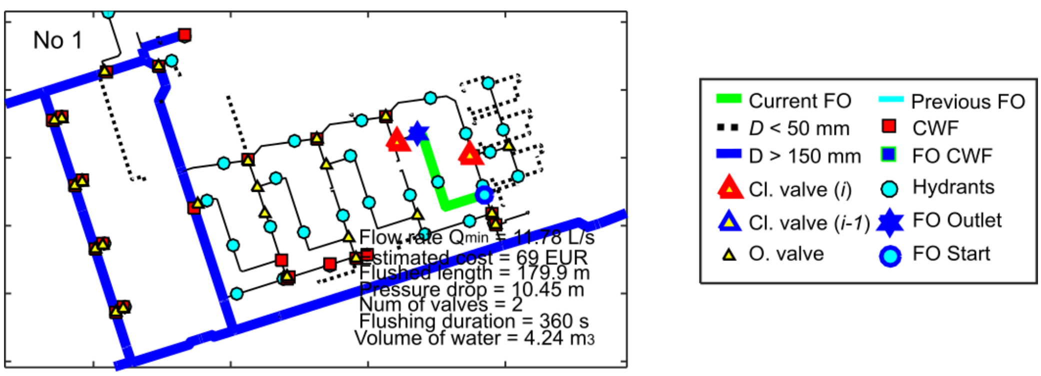

Figure 23 Zone 2 - Borrendammehof 1 Amsterdam (Second stage), FPA: Flushing operation 1 for the second flushable subzone

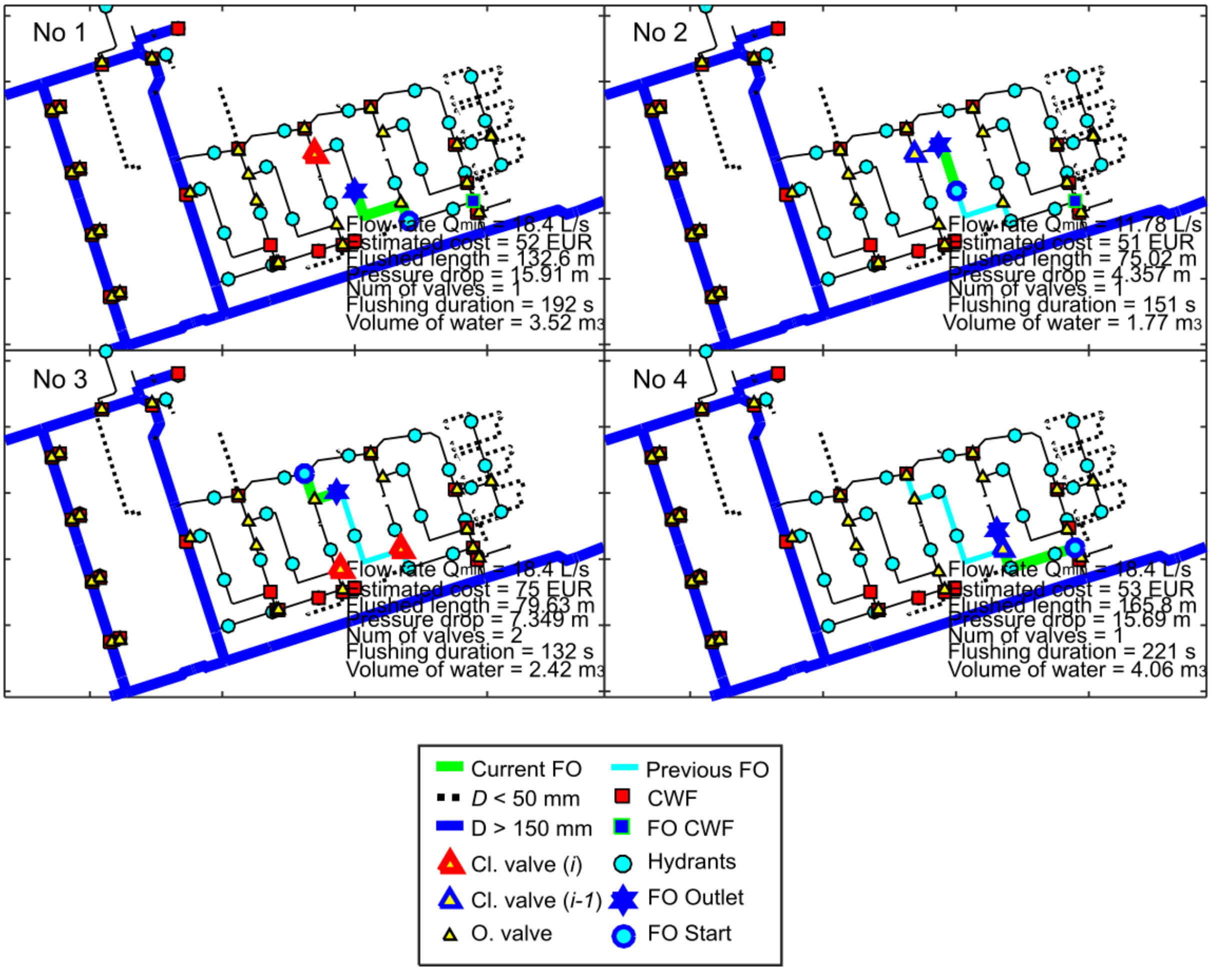

Figure 24 Zone 2 - Borrendammehof 1 Amsterdam (Second stage), FPA: Flushing operations 1 - 4 for the third flushable subzone

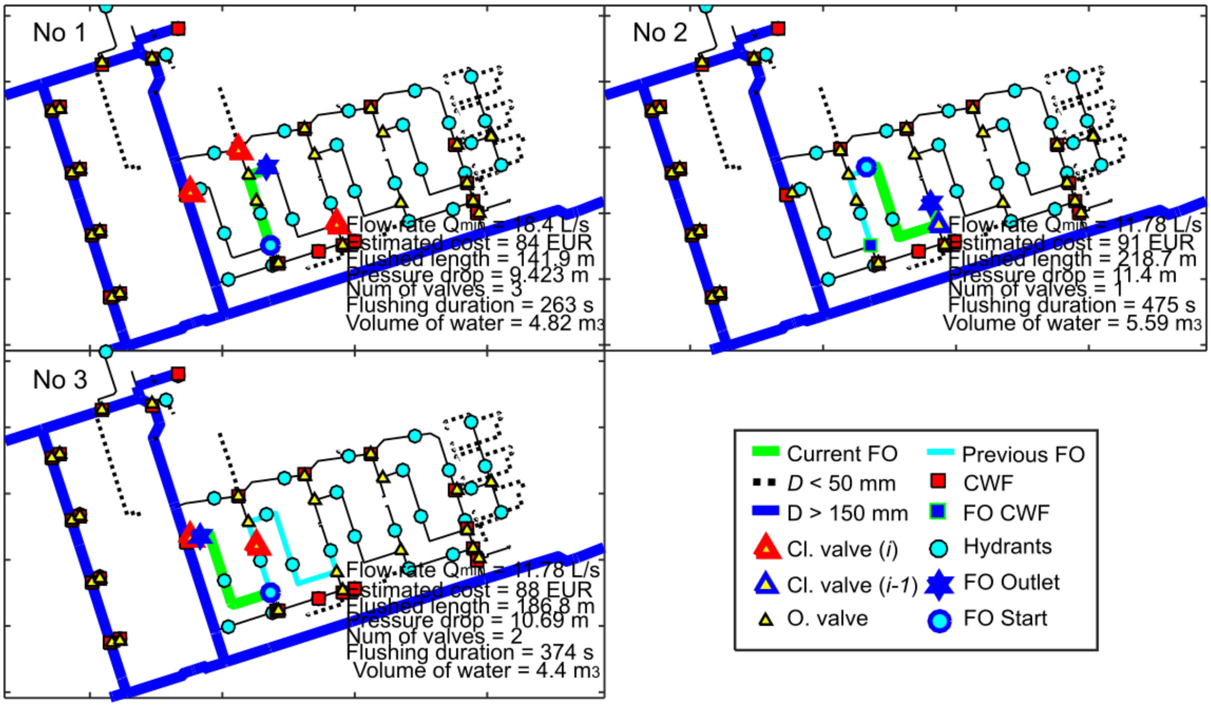

Figure 25 Zone 2 - Borrendammehof 1 Amsterdam (Second stage), FPA: Flushing operations 1 - 3 for the fourth flushable subzone

4.1.3. Zone 3 - Prof. H. Bavinckstraat 60

Using the FPA, flushing plans were derived for each of the available CWF of the four flushable subzones. An optimal combination of the subzone flushing plans is presented here. A North-South direction of the propagation was chosen as optimal for the Zone 3 Flushing plans.

Figure 26 shows the flushing operations for the small flushable subzone, in the northeast corner of the flushing zone. Figure 27 shows the flushing plan for the second subzone. Figure 28 shows the flushing plan for the third subzone. Figure 29 shows the flushing operation for the fourth flushable subzone. A total cost for the implementation of the flushing plans is estimated to be 838 € (82 € + 323 € + 401 € + 32 €).

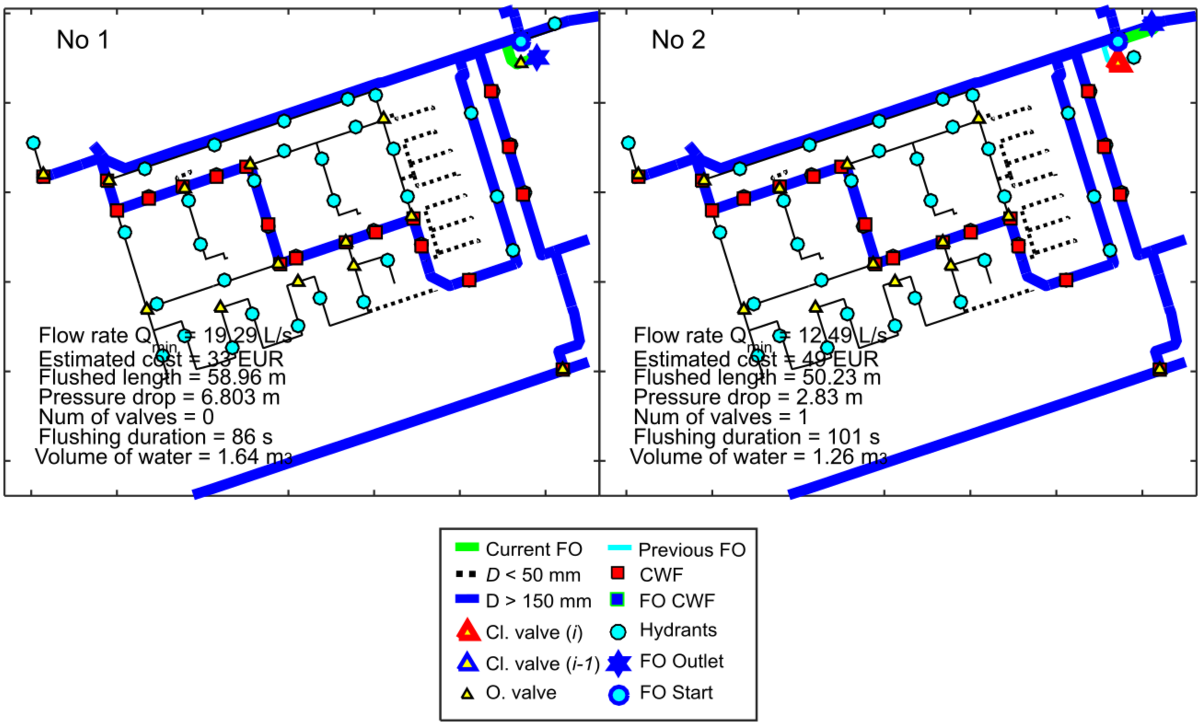

Figure 26 Zone 3 - Prof. H. Bavinckstraat 60, FPA: Flushing operations 1 – 2 for the first flushable subzone

Figure 27 Zone 3 - Prof. H. Bavinckstraat 60, FPA: Flushing operations 1 – 4 for the second flushable subzone

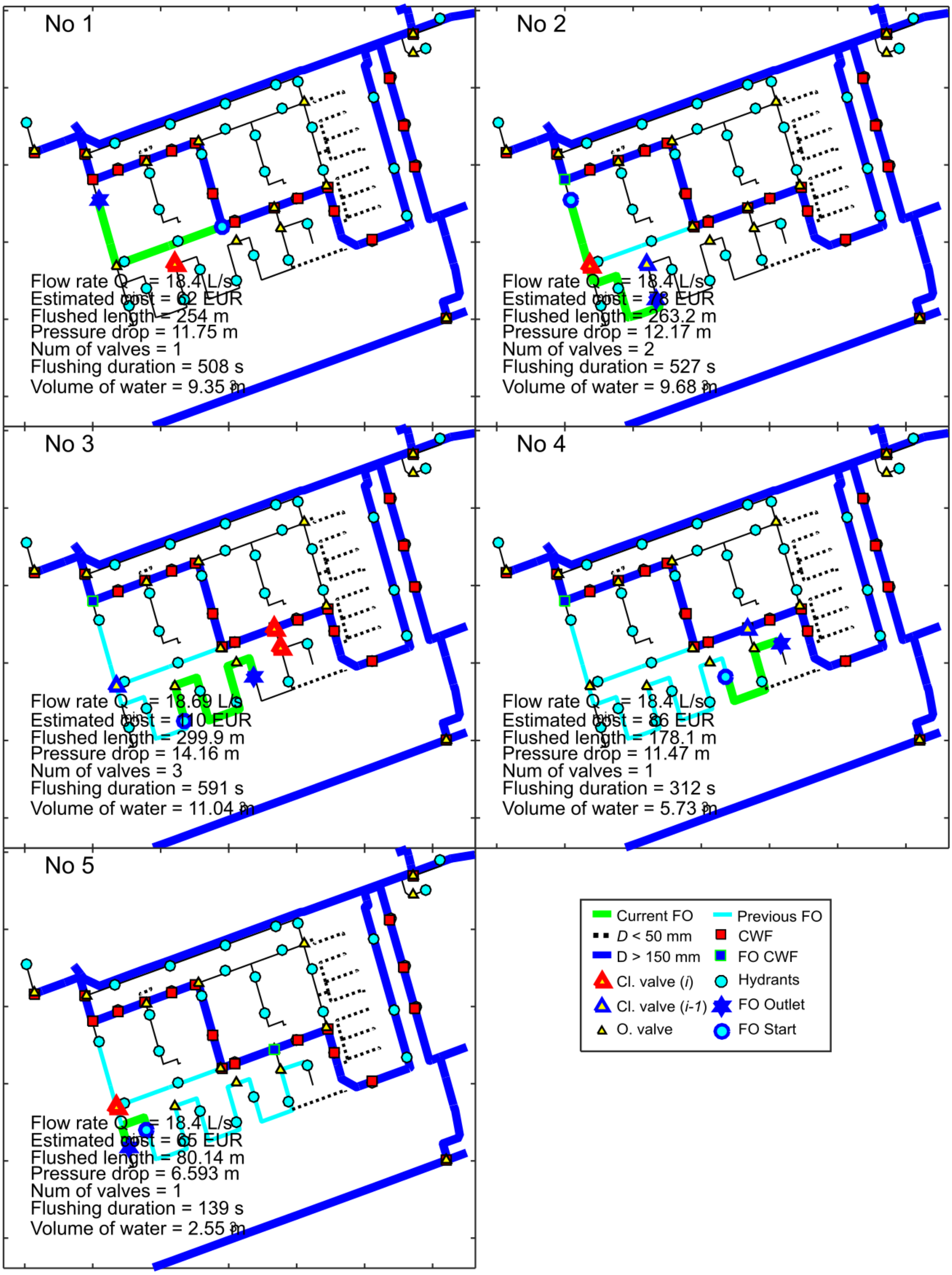

Figure 28 Zone 3 - Prof. H. Bavinckstraat 60, FPA: Flushing operations 1 – 5 for the third flushable subzone

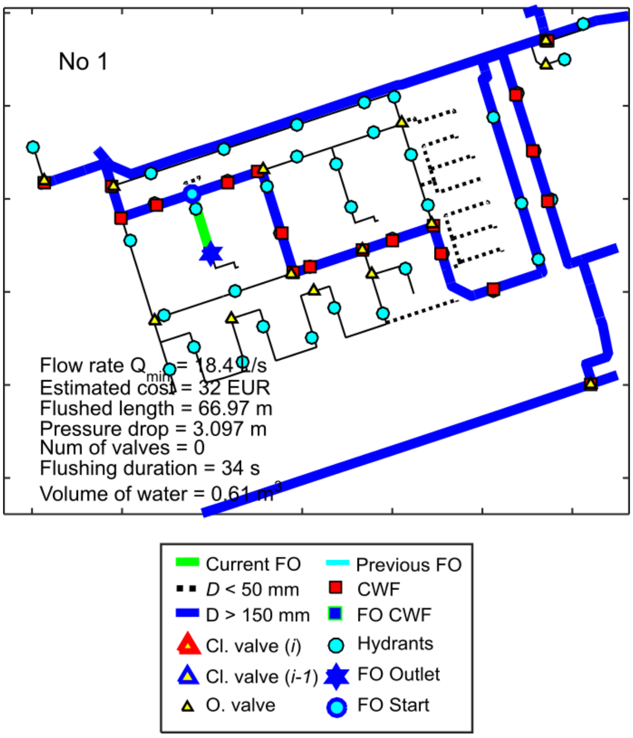

Figure 29 Zone 3 - Prof. H. Bavinckstraat 60, FPA: Flushing operation for the fourth flushable subzone

4.1.4. Zone 4 - Louis Raemaekersstraat 21

Using the FPA, flushing plans were derived for each of the available CWF of the three flushable subzones. An optimal combination of the subzone flushing plans is presented here. A North-South direction of the propagation was chosen as optimal for the Zone 4 Flushing plans.

Figures 30 - 31 show the flushing plans for the first subzone, in the northeast corner of the flushing zone. Figures 32 - 34 show the flushing plan for the second, western subzone. Figures 35 - 36 show the flushing plan for the third subzone. A total cost for the implementation of the flushing plans is estimated to be 1983 € (550 € + 845 € + 588 €).

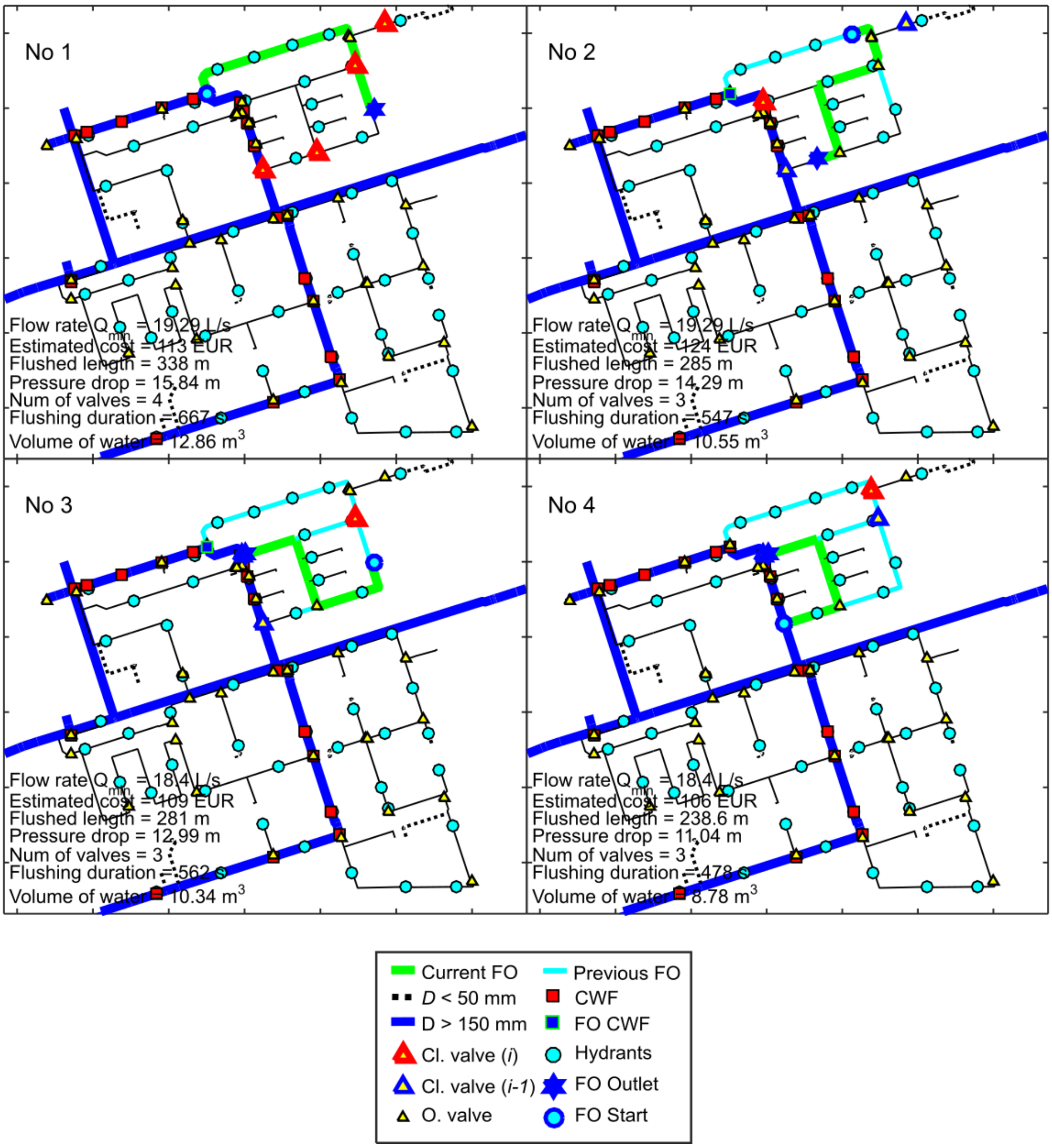

Figure 30 Zone 4 - Louis Raemaekersstraat 21, FPA: Flushing operations 1 – 4 for the first flushable subzone

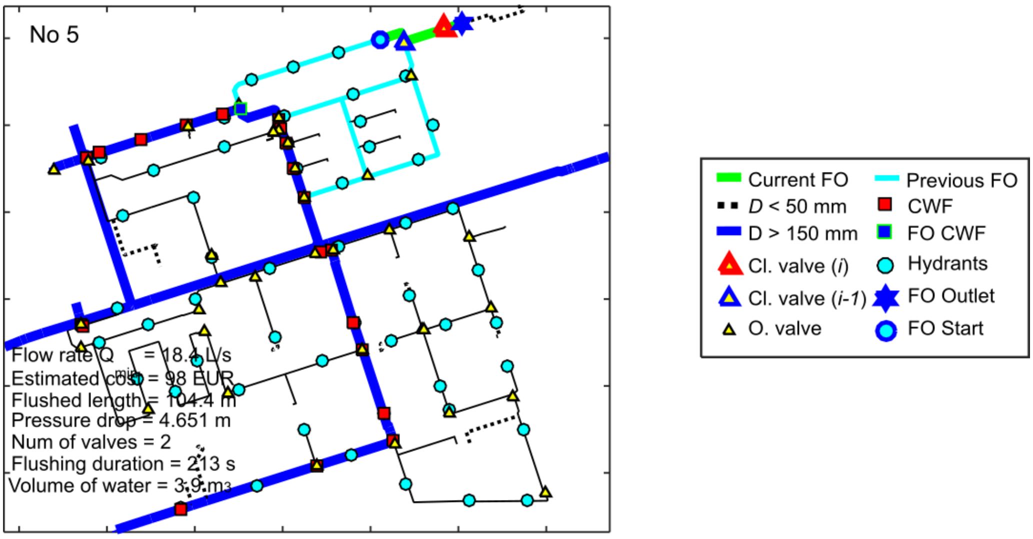

Figure 31 Zone 4 - Louis Raemaekersstraat 21, FPA: Flushing operation 5 for the first flushable subzone

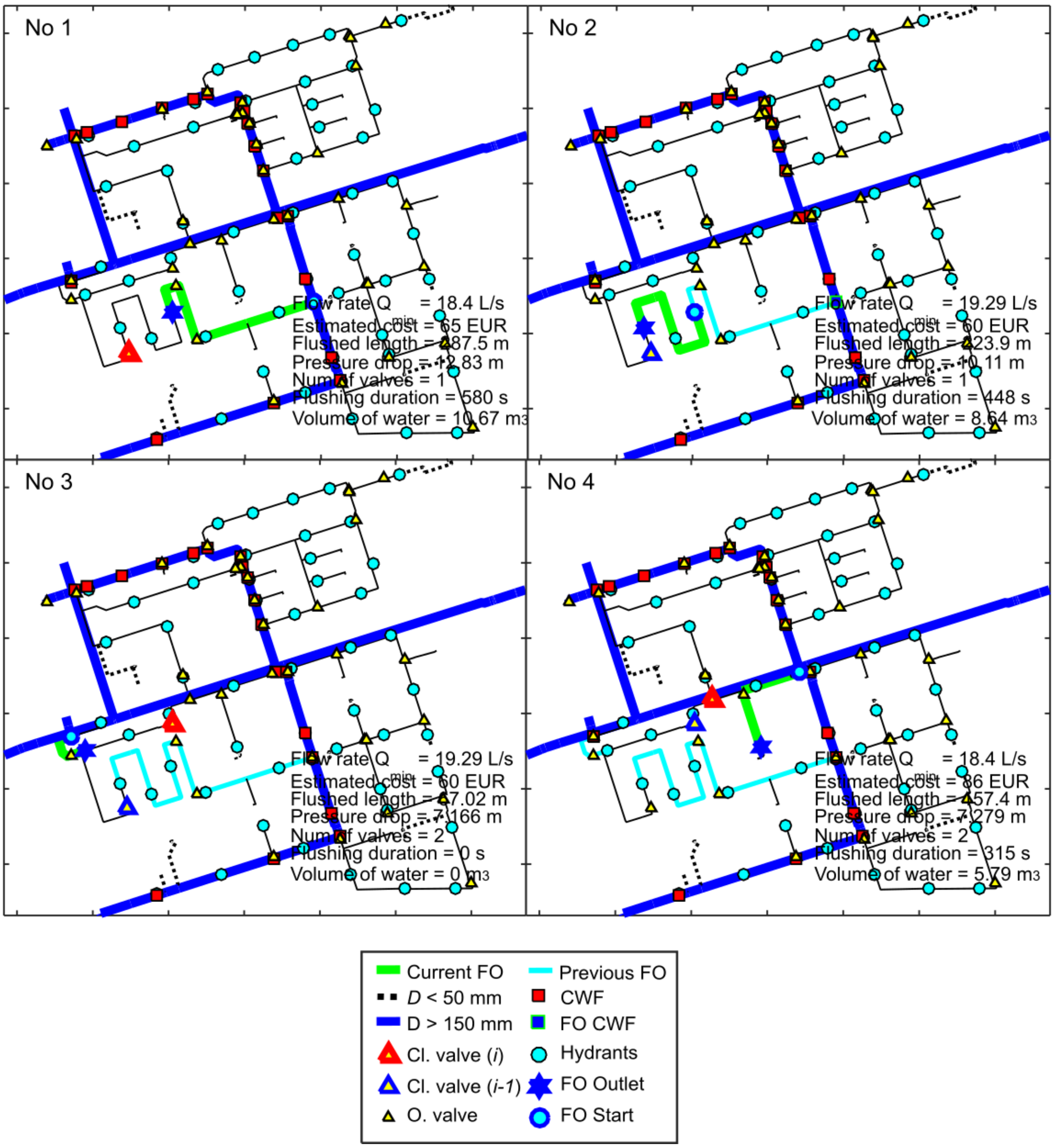

Figure 32 Zone 4 - Louis Raemaekersstraat 21, FPA: Flushing operations 1 – 4 for the second flushable subzone

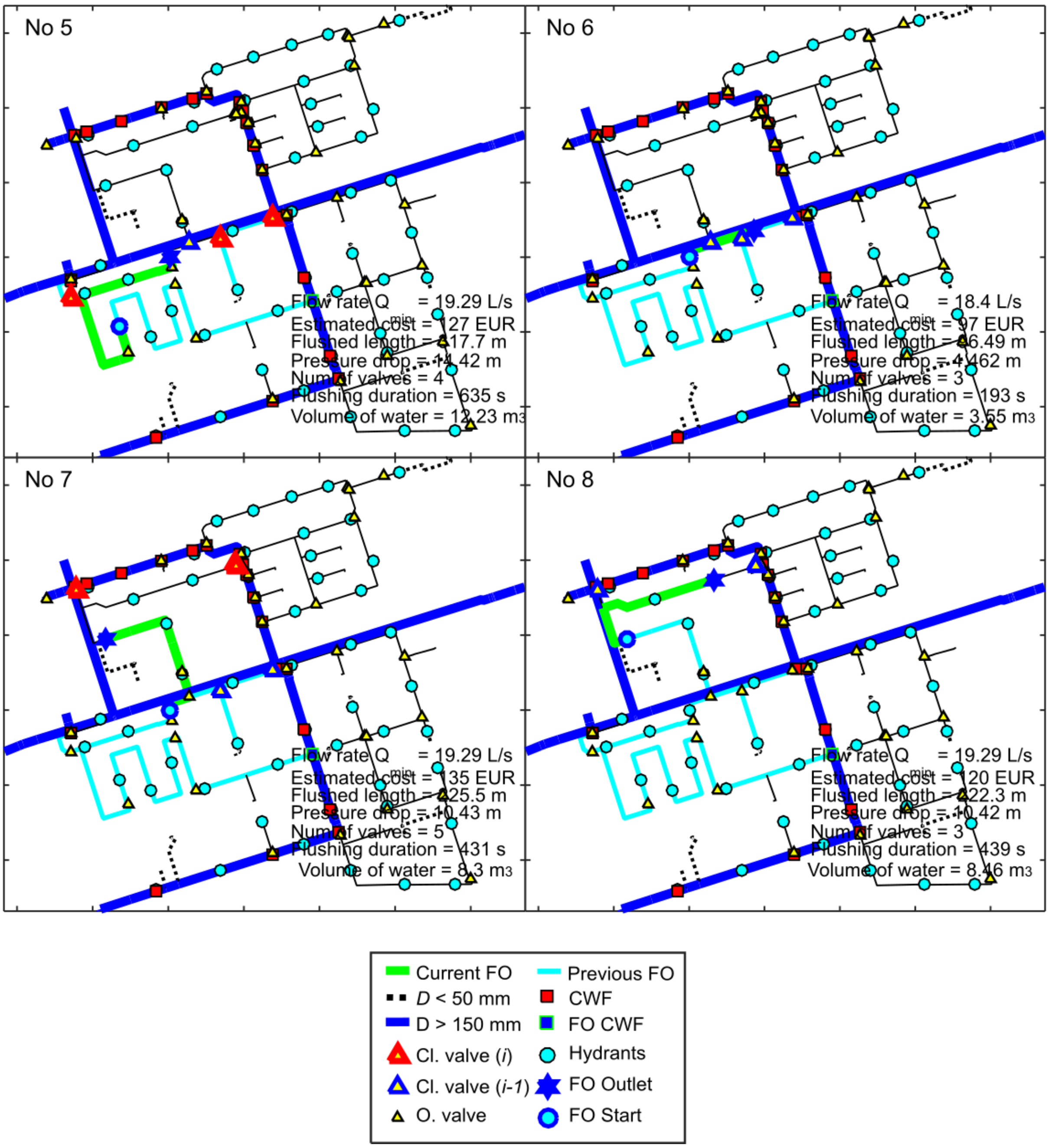

Figure 33 Zone 4 - Louis Raemaekersstraat 21, FPA: Flushing operations 5 – 8 for the second flushable subzone

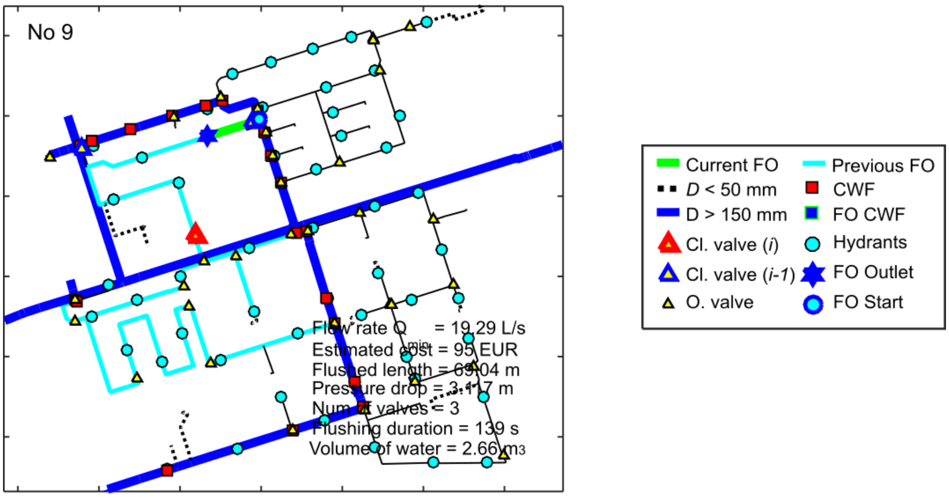

Figure 34 Zone 4 - Louis Raemaekersstraat 21, FPA: Flushing operation 9 for the second flushable subzone

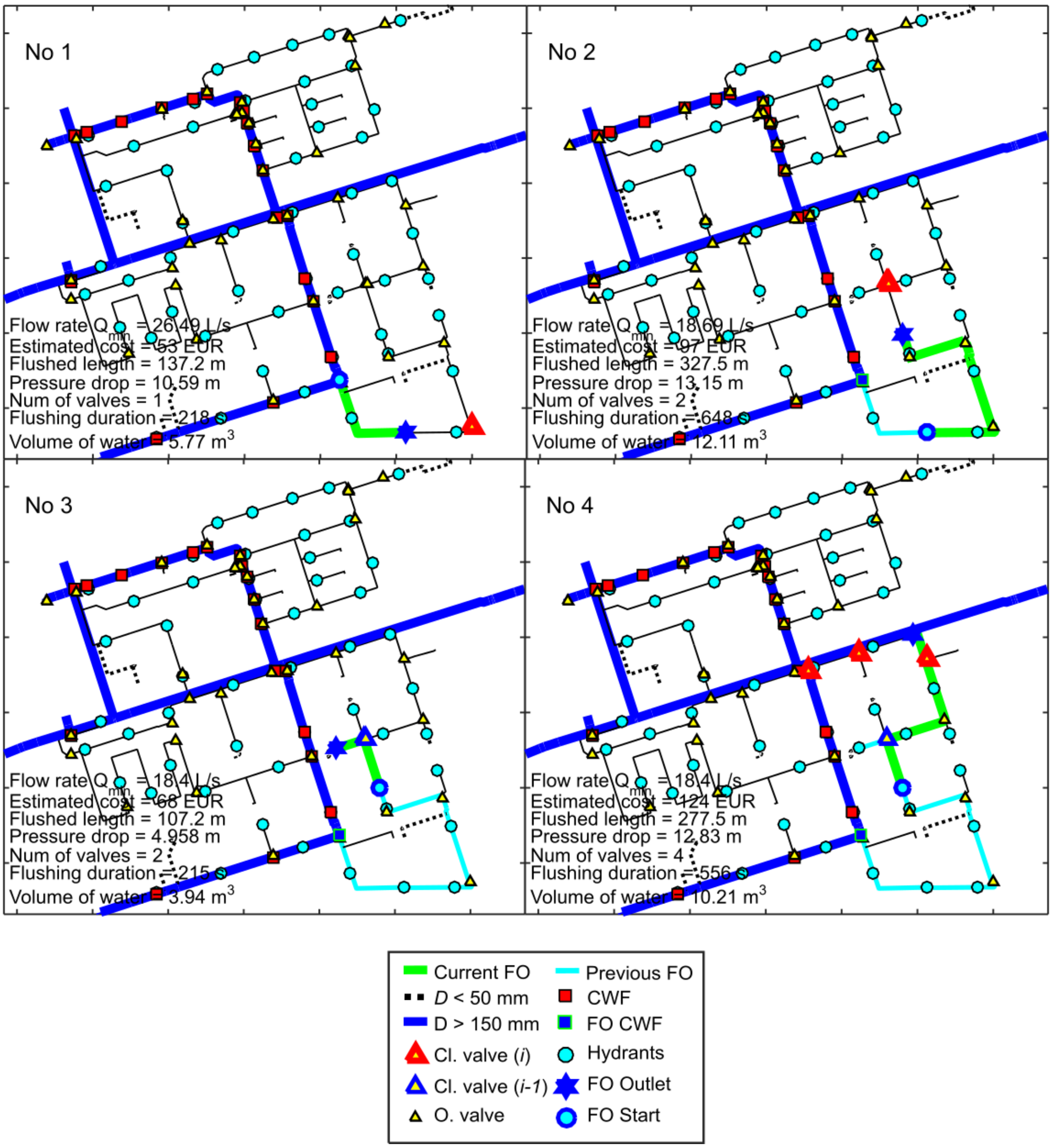

Figure 35 Zone 4 - Louis Raemaekersstraat 21, FPA: Flushing operations 1 – 4 for the third flushable subzone

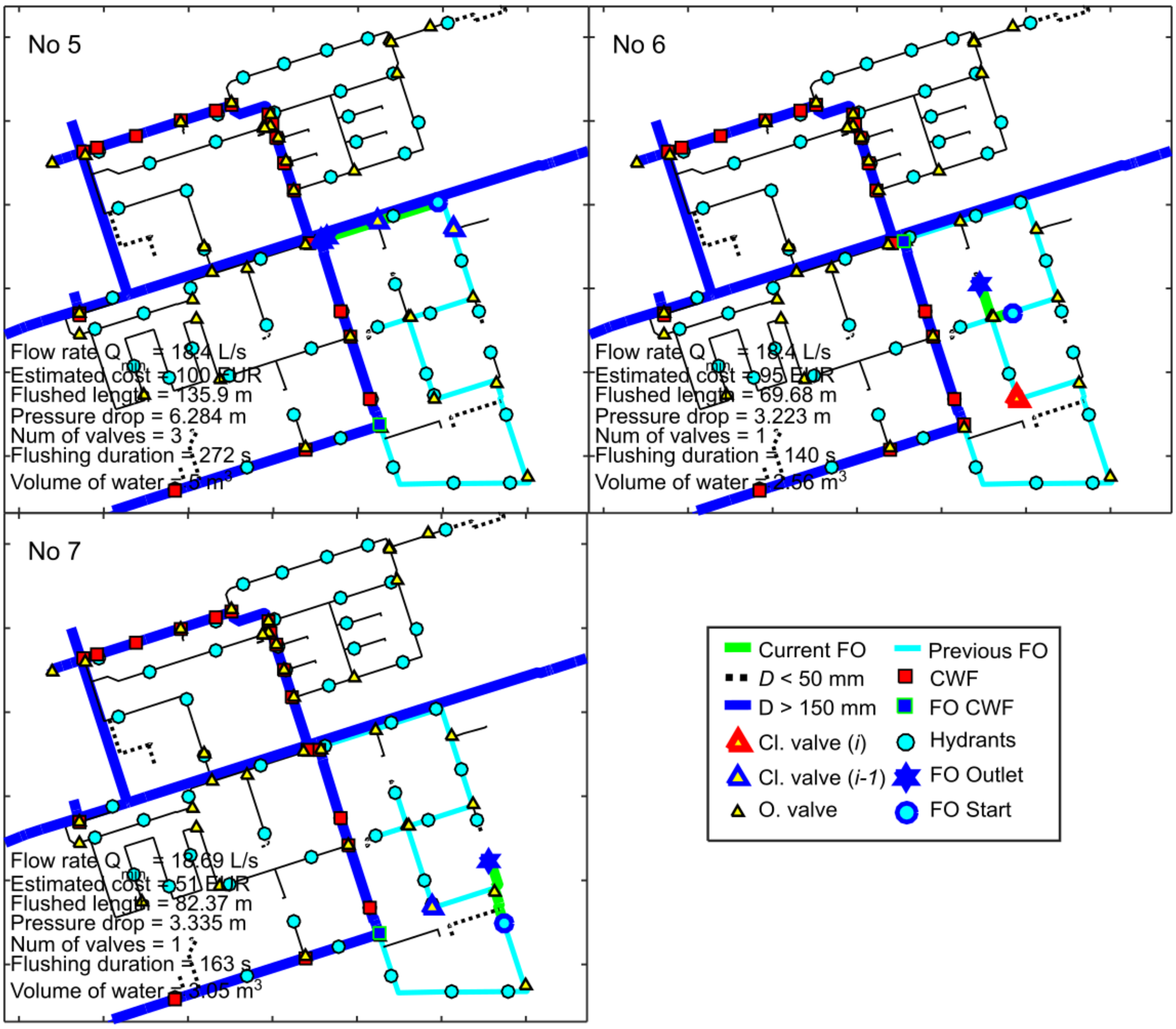

Figure 36 Zone 4 - Louis Raemaekersstraat 21, FPA: Flushing operations 5 – 7 for the fourth flushable subzone

4.2. Comparison FPA vs Existing flushing plans

This section is dedicated to the validation of the FPA and the comparison of the FPA derived flushing plan, with the existing manually derived. Flushing zone Jan Goeverneurhof 4, with existing flushing plan, was used for this purpose. The goal was to estimate the cost reduction and overall efficiency improvement, achieved when using FPA instead of the manual approach.

Several performance indicators (PI) were used for the comparison: the number of valve manipulations, effective flushing duration (duration of the flushing without valve manipulations and FO setup time), water expenditure and cost estimate. However, some crucial parameters were not comparable, e.g. the time needed for the derivation of the flushing plan. The FPA can deliver a flushing plan in roughly a minute, while it can be only estimated how much time is needed for the Waternet technicians to derive a flushing plan (hours?). Furthermore, the FPA relies on the hydraulic calculations of the pressure drop, where the model roughness data play a crucial role. On the other hand, manually derived plans, did not account for the hydraulics of the pipe flow, therefore it is questionable whether the 1.5 m/s minimal velocity can be achieved in the defined flushing operations. To allow for an unbiased comparison of the estimated costs, FPA_mod was used to derive a flushing plan using the flushing length constraint (like in manual plans), so the number of FOs would be similar (more details in 4.2.2.).

The section is structured in the following manner: in the subsections 4.2.1. and 4.2.2. the manual and FPA (and FPA_mod) flushing plans are presented, respectively. For the sake of brevity, complete flushing plans only for the subzone 3 are presented, which was the most looped subzone in the whole flushing zone. Additionally, the importance of proper valve manipulations is highlighted through an example of valve closure issue present in the manual plans. Subsection 4.2.3. is dedicated to the comparison of the computable PIs, for the subzone 3 of the validation flushing zone.

4.2.1. Manual flushing plans

Manual flushing plans for the flushing zone Jan Goeverneurhof 4 were extracted by Gerrit van Vliet, from the Mapkit web app. Within the Mapkit, the flushable parts of the specific flushing zone are represented with light green color. Current FOs are represented as purple lines, the currently closed valves as red triangles and outlet hydrants as red circles.

Figure 37 shows the screenshots of the manually derived flushing operations for the subzone 3, located at the west of the Jan Goeverneurhof 4 flushing zone. The flushing plan for this subzone is made of 8 FOs.

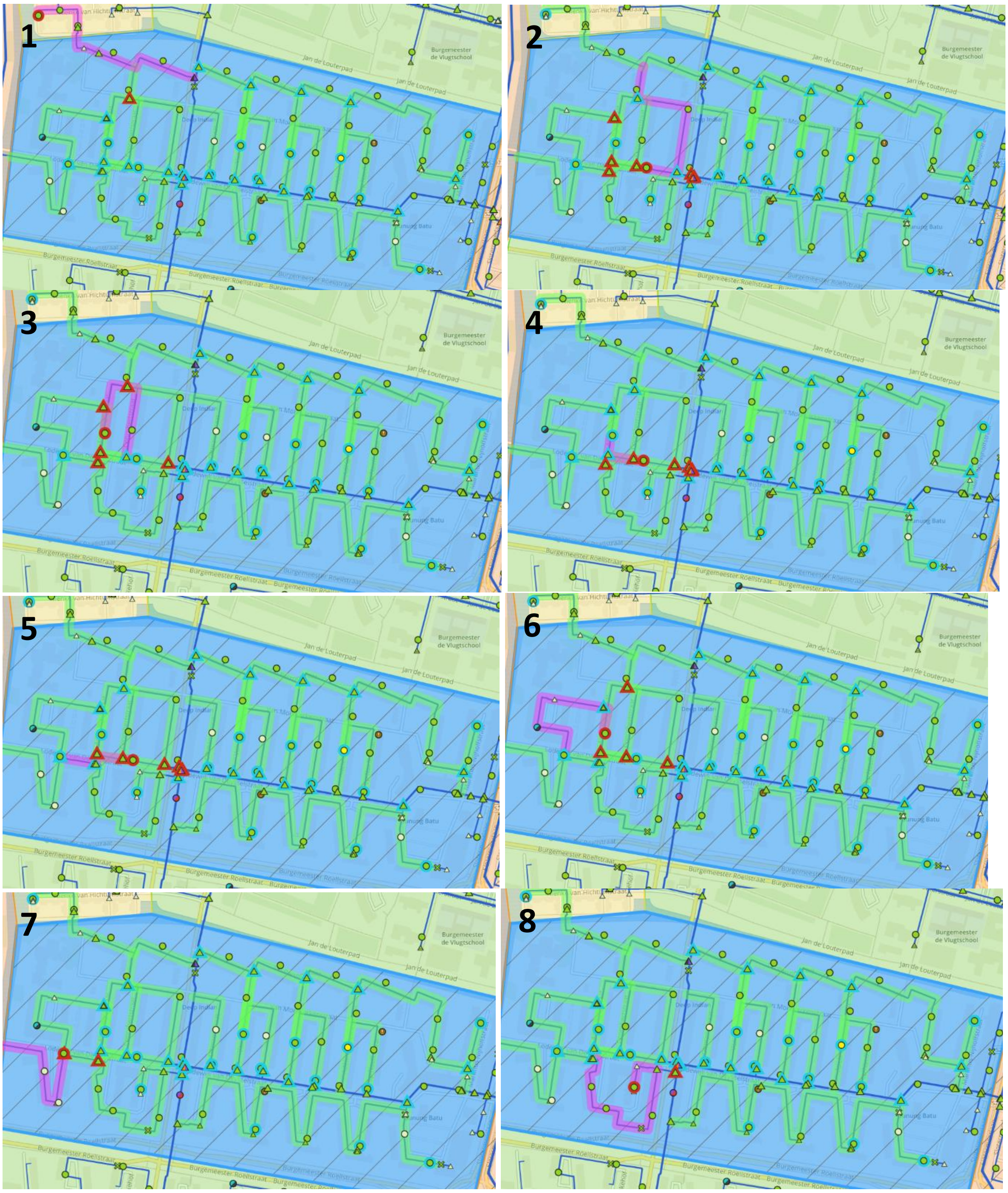

Figure 37 Validation zone - Jan Goeverneurhof 4, Manually derived: Flushing operations 1 – 8 for the third flushable subzone

For each FO the flushing length is determined and shown in the Mapkit app. The minimal flushing flowrate (**Q_{min}**) is defined after the FO is traced, where the user should find the maximum diameter in the flushed pipes and use it to determine the **Q_{min}**. Due to the fact that the pipe hydraulics are not accounted for in this manner, the user can easily define a flushing operation in which the velocity criterion is not satisfied, due to the insufficient upstream head. This leads to variable flushing effectiveness in terms of the discoloration removal. To overcome this issue, the FPA iteratively performs the hydraulic computations and maximizes the usage of the available head at the upstream end of each FO.

Furthermore, in the existing flushing plans for the validation flushing zone, it was observed that the valve manipulations were not adequately defined in several instances. An example is shown in Figure 38, where the valve to the south of the outlet hydrant was set as open (instead of closed). Thus, it can be estimated that only the small portion of the water flowing out of the hydrant came from the purple colored pipes, while the bulk was provided from the larger pipe in the vicinity of the hydrant. Consequentially this could be characterized as false flushing, where the target pipes were not flushed.

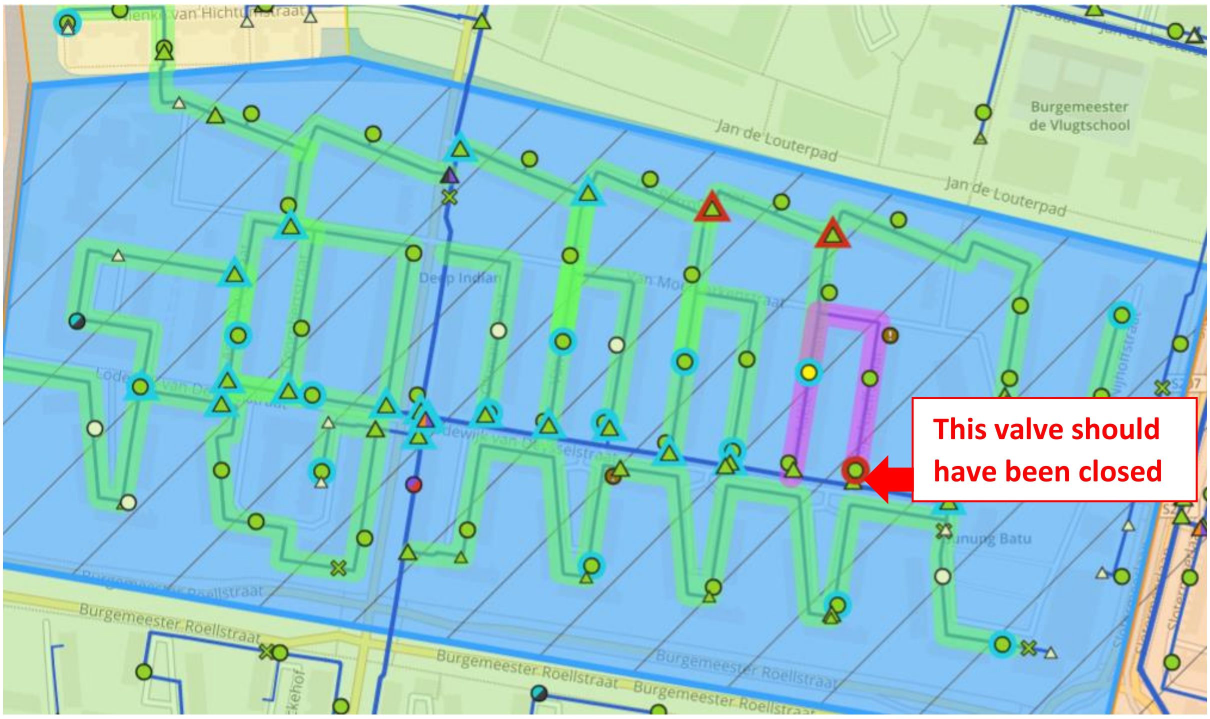

Figure 38 Validation zone - Jan Goeverneurhof 4, Manually derived: Example of false flushing due to the inadequate valve manipulations.

The value of the Performance Indicators (PI) were computed for the manually derived flushing plans (and subzone 3) are shown in Table 1.

Table 1. Performance indicators for the existing manually derived flushing plan for the subzone 3 of the Jan Goeverneurhof 4 flushing zone

Performance Indicators (PI)	No. valve manipulations [/]	Flushing duration (effective) [h]	Water expenditure [m3]	Estimated cost [EUR]
Manual:	40	1.5	99.9	1173.846

4.2.2. FPA flushing plans

Using the FPA, flushing plans were derived for the same CWF, as in the manually derived plan, of the third flushable subzone of Jan Goeverneurhof 4 flushing zone. Figures 39 - 40 show the derived flushing plan. The presented flushing plan for this subzone is made of 12 FOs.

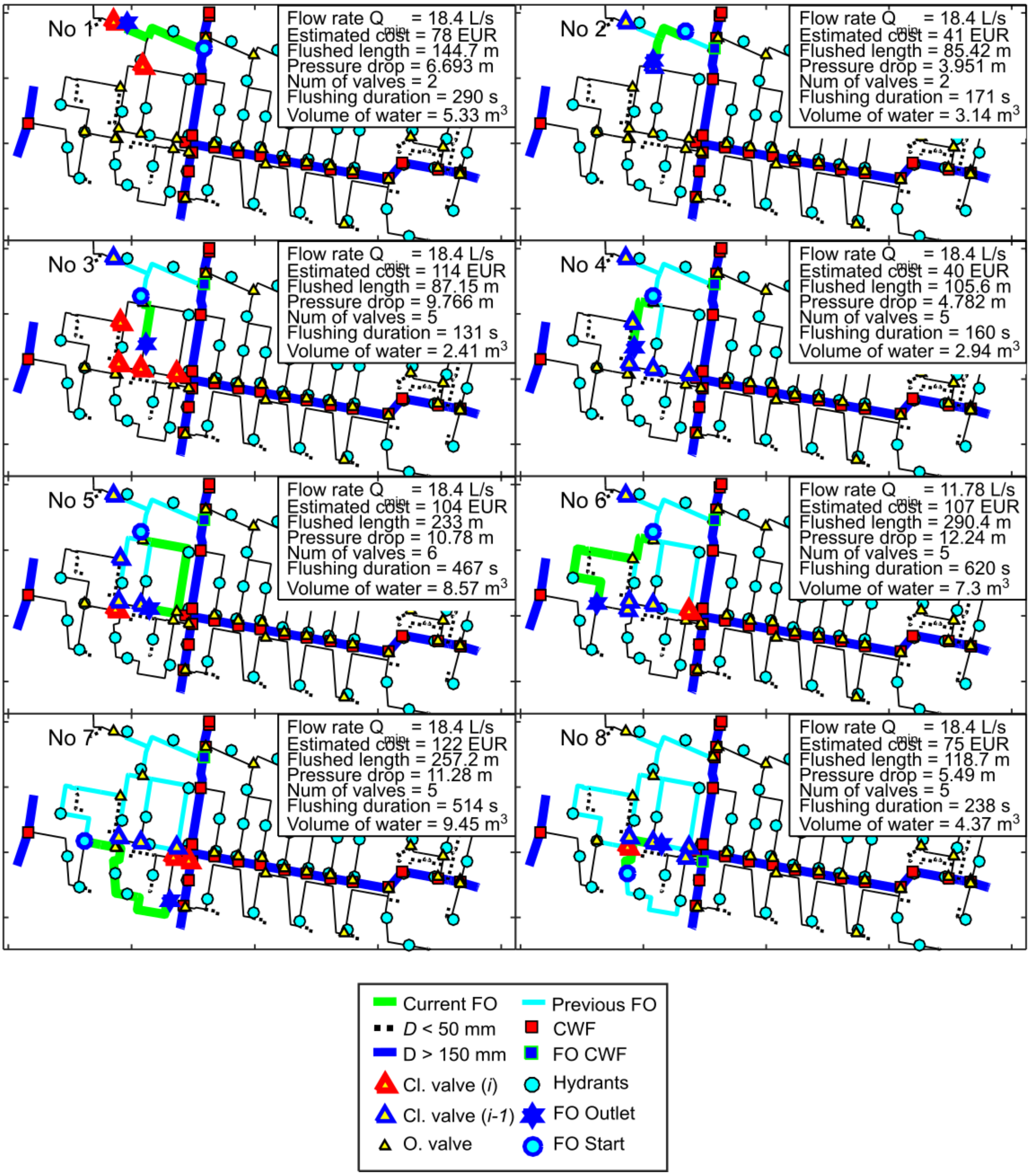

Figure 39 Validation zone - Jan Goeverneurhof 4, FPA: Flushing operations 1 – 8 for the third flushable subzone

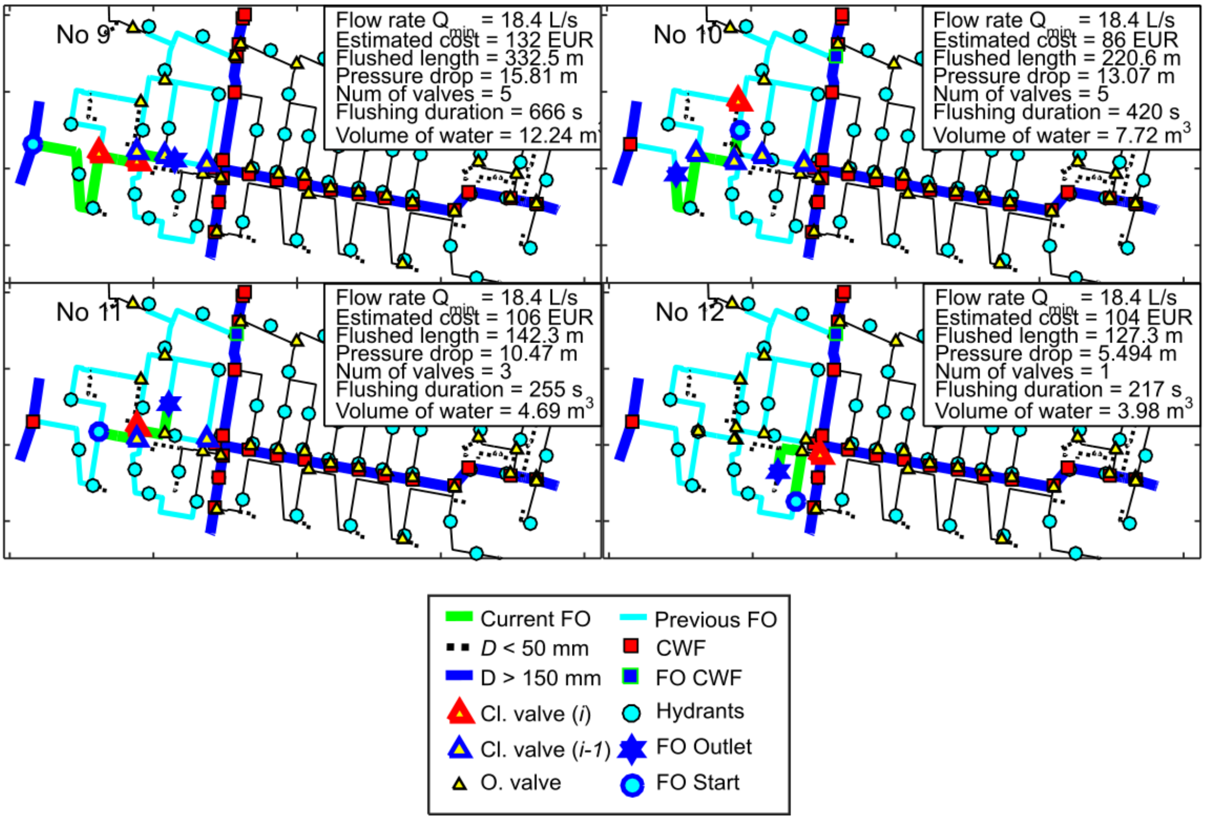

Figure 40 Validation zone - Jan Goeverneurhof 4, FPA: Flushing operations 9 – 12 for the third flushable subzone

When compared to the manually derived plans, FPA produced 50 % more FOs for this particular flushing subzone (12 instead of 8). The reason is that the FPA used hydraulic-based constraint for the flushing length, whilst within the manually derived plans only the length criteria was used. Thus, the FPA produced FOs with shorter length, leading to the larger number of FOs in the flushing plan. However, for the FOs derived with the FPA it can be stated that the minimal velocity criterion (1.5 m/s) is guaranteed in all flushed pipes, which is not the case for the existing, manual plans. But, due to the fact that more FOs were needed, the overall time of the flushing plan implementation is increased for the time needed for the extra flushing operation setups. Thus, the estimated cost of the flushing plan, derived with the FPA, is just slightly lower to the cost of the manual flushing plans (Table 2).

To highlight the benefits of the flushing plan optimization, performed within the FPA, a modified FPA (FPA_mod) was used to derive the new flushing plan for the analyzed subzone. Within the FPA_mod, flushing length was used as a criterion for determining the total length of each flushing operation (like in manually derived plans).

The resulting flushing plan, derived with FPA_mod, is shown in Figure 41. The new flushing plan for this subzone is made of 8 FOs. However, it should be highlighted that FOs 2, 3 and 7 had pressure drops higher than 20 m.

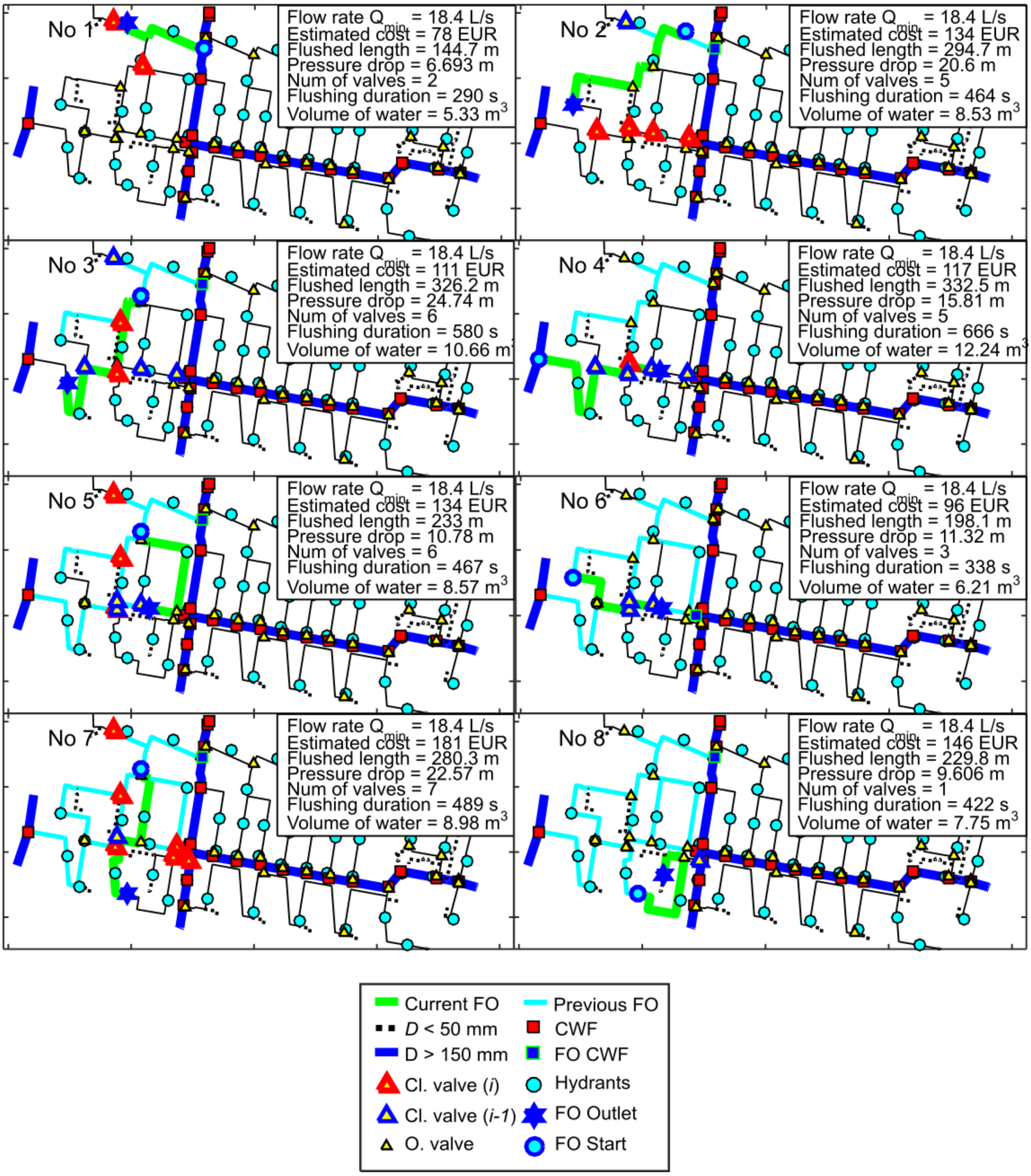

Figure 41 Validation zone - Jan Goeverneurhof 4, FPA_mod: Flushing operations 1 – 8 for the third flushable subzone

The value of the Performance Indicators (PI) were computed for the FPA and FPA_mod flushing plan (and subzone 3) and are shown in Table 2.

Table 2. Performance indicators for the FPA and FPA_mod flushing plans for the subzone 3 of the Jan Goeverneurhof 4 flushing zone

Performance Indicators (PI)	No. valve manipulations	Flushing duration (effective)	Water expenditure	Estimated cost
	[/]	[h]	[m3]	[EUR]
FPA:	33	1.15	72	1109
FPA_mod:	35	1.03	68.3	990

4.2.3. Comparison of the Performance Indicators

To get a quantitative estimate of the advantages of the FPA, over manually derived flushing plans, a comparison between the resulting flushing plans was made. Comparison is based on the several, comparable PIs: number of valve manipulations, effective flushing duration (duration of the flushing without valve manipulations and FO setup time), water expenditure and cost estimate. It is deemed that these PIs are sufficient for the assessment of the benefits of the FPA in terms of the end-result quality, the flushing plans.

PIs were computed for the subzone 3 of the Jan Goeverneurhof 4 flushing zone, for the manual derived plan, and for both the FPA and FPA_mod (modification of the FPA which uses the length constraint instead of the headloss computation). In Table 3, these PIs are shown along with the respective relative difference (Δ [%]) between the manual and FPA results. The relative difference was computed using the following equation:

$$\Delta_i\ [\%] = \frac{\left|PI_{man,i} - PI_{FPA,i}\right|}{PI_{man,i}} \cdot 100$$

Where the $PI_{man,i}$ is the i-th performance indicator value for manually derived flushing plan and $PI_{FPA,i}$ is the i-th performance indicator value for FPA (or FPA_mod) derived flushing plan.

The higher the value of Δ [%] is, the more savings in flushing plan implementation is achieved. In Table 3, the representative Δ [%] values, are colored in green, while the values in grey color correspond to the comparison between FPA_mod and manual plans which where not taken into account (due to the fact that pipe flow hydraulics were not satisfied).

Table 3 Comparison of the performance indicators between the Manually derived and the FPA (FPA_mod) derived flushing plans for the subzone 3 of the Jan Goeverneurhof 4 flushing zone

Performance Indicators (PI)	No. valve manipulations [/]	Flushing duration (effective) [h]	Water expenditure [m3]	Estimated cost [EUR]
Manual:	40	1.5	99.9	1174
FPA:	33	1.15	72	1109
FPA_mod:	35	1.03	68.3	990
Δ [%] - FPA:	**17.50**	**23.26**	**27.93**	**5.52**
Δ [%] - FPA_mod:	12.50	31.30	31.63	**15.66**

It can be seen that the FPA flushing plans need less valve manipulations (17.5 %), which is mainly due to the fact that the FOs have been designed in such manner so that the number of valve overlaps between two subsequent FOs Is maximized. Furthermore, the effective flushing durations are shorter (23.26 %). Consequently, the water expenditure is minimized (27.93 %). These effects are stemming from the fact that detailed pipe flow hydraulics have been integrated within the FPA.

Finally, the estimated cost was 5.52 % smaller for the FPA and 15.66 % for the FPA_mod. The value for FPA is lower as more stringent constraint was used to determine the maximum flushing length of each FO, the headloss computation. Thus, 50% more FOs were needed which lead to an increase of the total flushing time (but not effective flushing time) of 1 hour (4 * 900 s = 3600 s = 1 h ~ 120 €). To make an unbiased comparison, where the effects of the flushing plan optimization are highlighted, the estimated cost was recalculated for the FPA_mod where flushing length was used as constraint instead of the hydraulic calculation of the head loss in the flushed pipes. The cost reduction is clearly higher with the FPA_mod, as the same number of FOs was needed as in the manually derived flushing plans.

However, it should be stressed out that FPA offers more advantages which were not analyzed here in detail. Some crucial advantages are listed here:

- Time needed for the flushing plan design (FPA = 1 min; Manually = unknown. Field technicians stated that even though the flushing plans are made prior to the field work, a significant amount time is spent at the field for the flushing plan verification)
- Improved valve manipulation control (see Figure 38)
- Improved flushing efficiency (velocity criterion satisfied throughout the flushing plan)

These characteristics could not be compared in a quantitative manner, at least not at this point. But, they support the conclusion that the FPA usage can significantly improve the efficiency and the quality of the flushing in the drinking water distribution systems.

5. Flushing zones – FPA implementation challenges

The implementation of the FPA on the test flushing zones was met by several challenges. Some of the issues stem from the input data derived from the EPANET model, while other are related to the nature of the problem and applied methodology within the FPA. Whilst the first can be addressed by better preparation of the input data, the later was successfully met by the flexibility of the FPA.

5.1. Brandkraan/Hydrant identification in the EPANET model

Within the EPANET model provided by the Waternet, in some Flushing zones, there were no detectable features of the hydrant nodes, which could be used within the preprocessing stage of the flushing planning algorithm for the hydrant identification. Furthermore, in Zone 1, some brandkraans had the characteristics of the demand nodes, with the base demand and demand pattern fields defined. For the sake of future usage of the EPANET model, these issues should be addressed.

As a result, brandkraan/hydrant nodes were mostly manually identified. Manual identification process was time consuming as it was necessary to cross-check the EPANET model with the GIS model within the Mapkit webapp.

5.2. Mismatch between EPANET model and the Mapkit GIS model

During the input data analysis occasional mismatches between the EPANET and Mapkit GIS models were detected. Mismatches are listed here:

Zone 1 - Sleutelbloemstraat 34:

1. (Missing in EPANET) All HAAKSE KLEPDIENSTKRAAN OPGEBOUWD valves
2. (Missing in EPANET) Brandkraan 14691 – a nearby junction node is declared as a Hydrant.
3. Leiding 7194417 – is manually defined as a flushable pipe although the diameter is 202 mm. This is done since the pipe is positioned amid the flushable subzone.

Zone 3 - Prof. H. Bavinckstraat 60:

1. (Missing in Mapkit) Brandkraan in Prof. H. Bavinckstraat near the end of the street (next to the Afsluiter 74598). In the EPANET model a node with the Brandkraan characteristics (elevation -0.8 m) is present.

5.3. Flushing segments with pressure drop > 16 m

While Zone 2 was used for the FPA testing, it was realized that due to the high values of the pipe roughness, and variation of the pipe diameters within the flushing segments, a $V \geq 1.5\ m/s$ could not be achieved for over 20 % initially detected flushing segments. Thus, these flushing segments could not be used as building blocks for flushing operations. This has lead to the derivation of the flushing plans which did not cover the flushable parts of the Zone 2.

To overcome this issue, FPA was used in a different manner, where the geometric criteria (Section 2.1) for the flushable pipe diameters was modified. Instead of the original $50\ mm \leq D \leq 150\ mm$ criteria, two sets of the flushing plans were derived by segregating the diameter condition to $50\ mm \leq D < 128\ mm$ and $128\ mm \leq D \leq 150\ mm$. By combining these two flushing plans, all the flushable parts of the Zone 2 could be covered with flushing operations defined in accordance to the necessary hydraulic criteria. The derived results were satisfying, showing that a certain flexibility can be achieved by simple input parameter modifications of the FPA.

6. Flushing zones design optimization

Current flushing zones of the Amsterdam drinking water distribution system are defined in respect to topological characteristics of the network and geographical characteristics of the city area (e.g. roads, canals, bridges, etc.). One of the points raised by the Waternet, during the development of the FPA, was regarding the possibility of using the FPA to redesign the actual Flushing zones, and even optimize them. However, the criteria for optimization, and redesign, were not provided or analyzed in detail. In brief discussion it was concluded that multiple criteria could be used to address this issue, ranging from hydraulic/water quality based (e.g. the expected area of pollution transport in respect to the origin and flow conditions) to practical (e.g. time needed to flush a certain flushing zone). Due to the complexity of this problem, it is paramount to identify the key criteria and their interdependencies in order to allow for the design of a practical solution, capable of improving the water quality related services provided by the water utilities.

Even though criteria are not yet defined, a simple and practical solution can be developed with the current version of the FPA. The solution is based on the fact that FPA segregates each input Flushing zone into several flushable subzones. Each of the flushable subzones is separated from the rest of the network with pipes with diameter larger than 150 mm. Physically, flushing subzones are parts of the secondary and tertiary drinking water distribution network which are used to distribute the water to the customers. It can be assumed that the water will rarely flow from one flushing subzone to another. Thus, if the discoloration originates from the pipes within a particular flushing subzone (rusty pipes), it is deemed that the majority of the material that causes the discoloration will remain in the same flushing subzone. Furthermore, this implies that once the discoloration is located within one flushing subzone, of any flushing zone, it is probably sufficient to flush only the particular subzone. However, the turbidity should be monitored in the neighboring subzones in order to validate the given assumption that the discoloration remained in the source subzone.

By proceeding in this manner, it is deemed that the better control of the flushing actions will be achieved. The presented rationale is especially applicable in the cases where the flushing actions are performed to mitigate a localized issue, reported by customers (active response to customer complaints). However, further research is needed to verify the given assumption about the local character of the discoloration.

7. Conclusions and final remarks

Flushing planning algorithm FPA was derived to support and optimize the derivation and implementation of the flushing plans. FPA is designed in accordance to the best management practice used in Waternet for the flushing procedures. Furthermore, the FPA introduces novel hydraulic based design of the flushing operations, where the length of each flushing operation is defined in respect to the available upstream head and geometric properties and roughness of the flushed pipes.

Five flushing zones of the city of Amsterdam were used for the FPA testing. Multiple variants of the flushing plans for the flushing of the chosen flushing zones in the city of Amsterdam, have been defined automatically with the FPA. Optimal flushing plans, in terms of the minimal implementation cost, are analyzed here. Furthermore, one flushing zone was used for the validation of the FPA and comparison of the resulting flushing plan with the existing manually derived plan. The comparison is based on the four performance indicators (PIs). It was shown that the flushing plans derived with the FPA, need 17.5 % less valve manipulations, are 23.26 % shorter in terms of the effective flushing duration time and use 27.93 % less drinking water for the actual flushing. These PIs indicate that the FPA can significantly reduce the cost of the drinking water network flushing, by optimizing the flushing plans, while at the same time the control and efficiency of the flushing procedures is guaranteed.

Furthermore, the flushing plans can be derived quickly with the FPA, thus saving hours of technicians and engineers time. Moreover, the valve manipulations for each flushing operation are automatically designed according to the governing constraints, hence false flushing events can be avoided. Also, by employing hydraulically based approach in flushing plan design, the flushing efficiency is assured throughout the network. Finally, it can be concluded that based on the presented results, the FPA usage can significantly improve the efficiency of the flushing procedures and lead to the cost reduction in the flushing plan design and implementation.

Regarding future modifications of the FPA, it is clear that the majority of the input data can be generated from the GIS model, except from the pipe roughness. In the EPANET model, pipe roughness values have been computed through model calibration procedure. It should be noted that these data are attributed with a certain amount of uncertainty, stemming from the fact that pressure measurements used for the model calibration have been collected in the limited number of points in the network. However, for the purpose of the flushing plan derivation, the uncertainty of the roughness data is deemed as acceptable.

Since there are certain discrepancies between the EPANET model and GIS Mapkit model, it is perceived that it would be more efficient to extract the input data, for the FPA, directly from the GIS model. The GIS model is updated on daily basis, thus it is more likely that it is a more accurate and reliable source of data, when compared to the EPANET model. Furthermore, by proceeding in such manner, the possible incorporation of the used algorithm, or any similar one, within any GIS models will be simplified in the future.