

Agile Design of Sewer System Control^{*}

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Abstract: We describe the first part of an attempt to include stakeholder participation in the design of a central automatic controller for a sewer system in a small pilot project (five subcatchments) and present lessons learned so far. The pilot is part of a project aimed at the improvement of water quality management through central automatic control of sewer systems and surface water systems.

Keywords: Centralised control, Automatic control (closed-loop), Urban systems, Directed graph, Agile design, MIMO.

1. INTRODUCTION

The main objective of this paper is the presentation of our attempt to include stakeholder participation in the design of a central automatic controller for a sewer system in a small pilot project. The pilot is part of a project aimed at the improvement of water quality management through central automatic control of sewer systems and surface water systems.

We start by providing a description of the background of the project, its aims and the characteristics of the region where this project takes place. The main point of interest in the project is the conflict between the constraints on the control actions on the one hand and the wishes of the stakeholders on the other hand.

The ideal solution would be to avoid all Combined Sewer Overflow (CSO) events, but this is impossible due to the constraints imposed by the existing infrastructure (pump capacities, in-system storage). An important point to keep in mind while reading this paper is that, in contrast to many other sewer systems (Campisano et al., 2000, Introduction), most Dutch sewer systems have active control of flows through pumps with local automatic (real time) control. The reason for this is the flat terrain that makes gravity flow driven systems all but impossible. This also means that the inflow to the Waste Water Treatment Plant (WWTP) is already limited by the capacity of the installed pumps. As a result the focus tends to be on limiting the CSO events during high flows, optimizing

supply of waste water to the WWTP during low flows and in both situations avoidance of strongly varying waste loads.

2. BACKGROUND

Recognition of the importance of water is spreading. In October 2000 the EU Water Framework Directive (Directive 2000/60/EC) was adopted. In 2007 the Dutch water boards, municipalities, water supply companies and representatives of the national government signed the “Nationale Bestuursakkoord Waterketen” (national agreement on management of drinking water and waste water). This agreement had as one of its aims innovation in the chain from ground water and surface water to drinking water to waste water and back into surface water, essentially a human made and controlled part of the hydrological cycle. As a result funding was specifically earmarked for innovation in water management. An example is the “Innovatieprogramma Kaderrichtlijn Water” (innovation program for the Water Framework Directive), abbreviated to IKW, instituted by the Dutch Ministry of Transport, Public Works and Water Management in 2008. A group that consisted of the water board Hollandse Delta and five municipalities in its territory was interested in exploring the possibilities for increased efficiency of the waste water treatment and water quality improvement offered by increased cooperation. Together with Deltares and Delft University of Technology (DUT) a proposal with the title “Integrale sturing afvalwaterketen en oppervlakte water Hoeksche waard” (ISAHW) was submitted for IKW, which was approved.

The aim of ISAHW is to study all avenues leading to improved water quality and to implement some of the solutions found in several pilot projects. One avenue would

^{*} Part of the project “Integrale Sturing Afvalwaterketen en watersysteem Hoeksche Waard” for which AgentschapNL (previously known as SenterNovem) provided a subsidy from the “Innovatieprogramma Kaderrichtlijn Water” of the Dutch Ministry of Transport, Public Works and Water Management

be centralized automatic control of the pumps in the sewer systems of the municipalities and the pumps that transfer sewage from those sewer systems to their respective WWTP's.

The island "Hoeksche waard" to which the project name refers lies in the Rhine Meuse delta. This island provides a location with clear physical boundaries that falls completely within the area of responsibility of one water board and one province. It is also divided into a relatively small number of municipalities (five). This makes it an interesting test case for cooperation. The area consists of polders. Surface water levels in the polders are controlled by pumping stations managed by the water board. This provides indirect control of the ground water level. In built-up areas the ground water level is often only one meter or so below the surface.

Ground level varies from -2 to +1 meters relative to Normaal Amsterdams Peil (NAP is the Dutch national reference level, its value is close to mean sea level).

Within each municipality there is a mix of sewer systems in use. We find Combined Sewer Systems (CSS), sanitary sewers, storm sewers and storm sewers where the initial, presumably most polluted inflow, is redirected into a sanitary sewers. The most common variant is CSS. The sewer systems of the municipalities are divided into separate networks with gravity driven flow. The lack of terrain gradient and the high ground water levels (often only a meter or so below the surface) restrict the amount of head that can be created within the system and this in turn limits the size of the gravity flow driven networks. To compensate for the lack of natural head these small networks are linked to each other and to a WWTP by pumping stations. In the project area there are multiple WWTP locations and pressure pipes linking multiple built-up areas to one WWTP.

Let us consider each gravity driven flow network as the underground water courses of a subcatchment and the surface area connected to it as the land area of that subcatchment. Note that only part of the surface area above the network discharges into the sewer system, precipitation may also flow to open water or groundwater. Each subcatchment has a certain amount of storage in the pipes of the sewer system (also known as in-system storage). For each such subcatchment the dry weather flow (dwf) that originates in houses and factories is usually modeled either as an average or as a fixed periodic discharge into the sewer. The flow due to precipitation is modeled by one or more rainfall-runoff relations associated with different parts of the connected surface (roofs, streets, parking lots).

Typical rainfall intensities in the Netherlands range from 0.1 to 10 mm per hour. Average annual precipitation is 750 mm. An event totalling 100 mm in 24 hours is considered an extreme event. The storage in terms of connected surface for the CSS subcatchments of the pilot project ranges from 7 to 14 mm. The dwf is modelled as 0.120 cubic meters per 24 hours per inhabitant of the connected area based on 2.5 inhabitants per dwelling. The pump capacity available for precipitation after deduction of the capacity used by dwf and transport from upstream subcatchments ranges from 0.6 to 4.6 mm per hour. These values are not unusual for Dutch systems. There

is one exceptional subcatchment where due to upstream overcapacity the net available capacity is -5 mm per hour.

As is usual in the field of sewer design pump capacity is given as pump discharge divided by connected area and storage is given as volume divided by connected area.

In general central control can be used to shift CSO events to less vulnerable areas and can be valuable to schedule pumps in dry weather conditions to achieve a steady flow to the WWTP. The purpose of ISAHW is to evaluate both the technical feasibility of central control and its potential gains in particular cases.

The efficiency of a WWTP, managed by the water board, may depend on the quantity and the waste load of the incoming wastewater (Rauch et al., 2005, page 402), but in current practice municipalities are free to transport waste water to the treatment plant whenever they wish, the only restriction is an upper limit set for each municipality by the water board.

Large parts of the systems are combined sewers, so if this upper limit is lower than the actual amount of waste water that needs to be transferred out of the system then a CSO may occur at some point in the system and pollute a water course. This impacts the water quality of open water, which is the responsibility of the water board.

3. THE PROJECT

The deliverables of the project to be supplied by DUT are a control algorithm and a module that implements this algorithm. It is intended for tests and demonstrations. This module must interface with two software packages: a sewer model implemented in Sobek-Urban (Deltares—Delft Hydraulics) with which it will be linked through openMI (Knapen et al., 2009) and a FEWS (Werner, 2008) application that will function as an intermediary between the municipal SCADA (Supervisory Control And Data Acquisition) system and the controller.

3.1 Control Related Concerns

The main concern of DUT within the project is the development of a form of central automatic control. We plan to explore both centralized automatic control within municipalities to minimize CSO and centralized control at the level of the water board to optimize use of available WWTP capacity. Both technical limits on possible improvements through centralized control/decision support and limits on organizational acceptance need to be established. We will concentrate on operational questions such as: "what can be done with current technology?", "how can this be fitted into the operational structure available?" and most importantly "will the controller be viable?".

The literature emphasizes definition of objectives of control in terms of auxiliary criteria such as overflow volumes or frequencies (Schütze et al., 2004; Schilling et al., 1996). These objectives are then translated into an optimization problem. Another approach is set out in Breur et al. (1997) where, for each system configuration (taking account of maintenance and breakdowns) a strategy for the use of distributed system storage is given that relates the fraction x of total system storage in use to the desired fraction f_k of

storage to be used in each subcatchment. The optimization then tries to achieve this distribution. We hope this will make immediate interpretation of the control system actions easier. Its operation also emphasizes that in a system where additional capacity to process larger events without CSO is considered too expensive, operation will need to be based on a best effort basis. With our curve based approach it is clear that there is a point where protecting one area makes CSO in another area unavoidable because keeping one fraction low will push others above one.

Any new options for the realization of strategic targets will of course need to be evaluated in a process that involves stakeholders outside of the municipalities and the water board. The project is after all an experimental pilot project. However, one group of stakeholders needs to be involved “early and often” because experience in earlier projects showed that in water management their acceptance is essential. These stakeholders are the operators and their managers who need to trust the system and may need to explain its actions to others.

In this project exploration of the system behavior through models and through a measurement campaign will run in parallel with our work on the controller. These results will need to be incorporated in the design as they become available. Moreover, we need to keep the operators and the managers of the systems to be controlled involved to make sure our implementation is usable and will be accepted. This precludes the use of a linear planning, design and implementation process.

The team at DUT is small, self managing and only deals with the control algorithm (read software), this allows for more flexibility there than in the other parts of the project. Faced with the need for development of a controller in parallel with the exploration of the system to be controlled and the need for acceptance by operators and managers, we saw a link with agile software development, where requirements are fluid and users/clients/owners are actively involved in the choice and ranking of features (Bessam et al., 2009; Abbas et al., 2008). Arguments for the importance of stakeholder involvement in general are given by Soncini-Sessa et al. (2007a,b).

3.2 Can we be Agile?

A popular software development methodology is known as *agile software development*, see for example Stober and Hansmann (2010). Conceptually it is the opposite of the older waterfall model of software development where the steps of requirement analysis, design, implementation and testing are often treated as separate and strictly ordered. In agile development these components are still present, but they are applied to evolving requirements. Starting from an initial requirements statement a small number of functions is selected for an initial cycle of analysis, design, implementation and testing. Thereafter many short iterations follow in which functionality is added and requirements are added, removed or refined. Moreover, testing and implementation are closely intertwined, tests may even be written before the code they are supposed to test.

Whether we can safely use agile techniques in our project is an important question. We base our answer on the

assumption that we will use the techniques to develop a control algorithm and software to demonstrate its properties, not to develop the final operational software. The operational software will be written when the behavior of the algorithm is acceptable to all stakeholders and a mathematical proof that the algorithm will behave as expected has been provided. Note that during algorithm development code will have been written to examine the behavior of the algorithm when linked to validated models of the sewer system. The tools developed to test the controller component of this software can be considered for reuse in the development of the operational software.

Now let us check the applicability of agile methods, for instance by the criteria mentioned by Turk et al. (2000). Most of their assumptions fit our situation. From the list of limitations they give only that of limited support for safety critical software might apply. We avoid this problem by insisting on a rigorous mathematical proof of correctness for the final algorithm and the use of an appropriate method for the development of the code for the final operational software.

The aspects of agile development we wanted to borrow are:

- short development cycles (iterations)
- functionality targets for each development cycle are negotiated with the users
- features are implemented only when their need has been established
- test driven development

We expect that differences in time scales (a measurement campaign takes time to set up and execute, staff availability constraints in a university differ drastically from those applicable to the other partners) will result in development cycles of varying length.

After the project setup, which consisted of a gathering of funding and signatures, there was an initial reconnaissance phase with meetings at each municipality to determine problems, gather data on the existing system, install monitoring equipment and perform baseline measurements. This overlapped with the first iteration in the control design. At the end of this phase a workshop was organized at Deltares to demonstrate aspects of centralized control/decision support and to decide on the length and direction of the second iteration for the control system. This was also an occasion to informally evaluate ways to increase organizational acceptance.

3.3 A project time line

The project as a whole involves much more than just the control component. Up to a point the traditional diagram from Schütze et al. (2008) where steps for the implementation for control of a sewer system are set out applies. However, this project is aimed at gaining practical experience with coordination and control, so the steps concerning cost effectiveness would not have their usual meaning. A more appropriate view is given in Fig. 1.

4. THE WORKSHOP

The aim of the project is to develop an experimental implementation of central control. All parties involved are

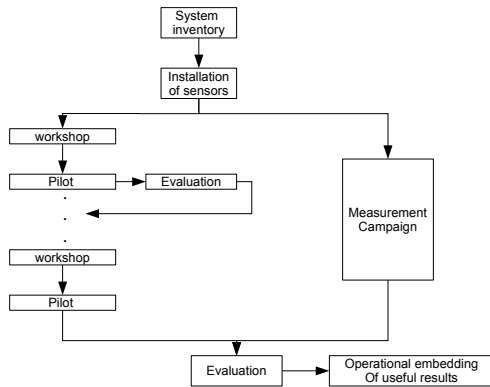


Fig. 1. Project time line

committed to the success of the project. Nevertheless, it will be necessary to maintain enthusiasm amongst the participants to keep the initial momentum.

As this is a project intended to evaluate the feasibility of central control up to and including a local experimental implementation, we need to take into account two groups of stakeholders, namely those potentially affected, should it be decided to start a new and larger project to implement operational central control and those directly affected by this project. For the moment we concentrate on the second group. This group consists of the decision makers at the water board and within the municipalities and of the operational staff that will be responsible for implementing the pilot project. Alexander (2003) emphasizes the importance of operators and maintainers as stakeholders.

During the workshop all participants had a computer at their disposal with special software to investigate the system and the controller. Placed in the context of a Participatory and Integrated Planning (PIP) Procedure as described in Soncini-Sessa et al. (2007a,b) the workshop was intended to act as a bridge between the conceptualization phase and the start of designing alternatives. It demonstrated the type of central control to be used at municipality level to the operational staff.

4.1 Context

Dutch sewer systems tend to be designed for and operated with local control. Pumps transfer water between subcatchments and from subcatchments to the WWTP. The close correspondence between design and operation results in efficient operation, but it also means that the concept of central control needs some introduction. Moreover, the current operation allows data gathering to be almost entirely separate from pump control. Local sensors control the pumps directly. Accumulated measurements are transmitted to a central post once a day. This methodology is deeply ingrained in both the technical system and the organization. One of the aims of the first workshop was to raise awareness of these aspects.

The workshop itself was centered around a number of different examples. Each example was modeled on an existing system from the working area of the project and

built around one control concept. In preparation for the workshop proper a trial session was held with personnel of Deltares and two representatives of the water board.

4.2 Method of central automatic control

True to the agile principles (features are implemented only when their need has been established) we implemented a fairly simple central feedback controller for one municipality for this first workshop. Later controllers at municipality level will be used to manage the sewer system and a higher level controller will assign quota for flow to the WWTP. The controller, called Composer, is described in Breur et al. (1997) and in more detail by van Leeuwen (2003, in Dutch).

This system is particularly appropriate because it allows tuning of the control parameters through manipulation of the curves along which the controller will attempt to guide the filling of the reservoirs. For Dutch sewer systems this turns out to be a fairly natural way of thinking about the system.

4.3 The model used

The system is a directed tree graph with inflow and storage at all nodes (except the root) and limited capacity on/off transport along the arcs towards the root where there is a constraint on total inflow into the root (the WWTP). If we have N_v vertices (the subcatchments) then we have $N_a = N_v - 1$ arcs (the pumping stations). This means we have N_v states (stored volumes) and N_a discrete inputs (0 for a pump that is off, 1 for a pump that is on). The volume varies continuously in time, but the control actions are taken at fixed times separated by a constant time step. The transport capacity of the arcs is relatively small when compared to the storage at the nodes and the peaks in the inflow. Currently the pumps are controlled by local bang-bang controllers with hysteresis. The connections in the system are represented by the incidence matrix M of the graph. We run for T time steps. The instants between steps are t_0, t_1, \dots, t_T . Each subcatchment receives an inflow p_k in time step $[t_k, t_{k+1}]$ and its internal storage at the end of this time step is labeled $v_{k+1,i}$. The internal storage of vertex i has an upper limit $v_{\max,i}$. If in a time step this value is exceeded then a CSO $s_{k,i}$ results. Each arc j has a pump capacity of $c_{\max,j}$. Pumps are restricted to be either on or off. For a given assignment of pumps represented by values $a_{k,j} \in \{0, 1\}$ the system evolution is given by

$$v_{0,i} = 0$$

$$v_{k+1,i} = v_{k,i} + p_{k,i} - s_{k,i} + \sum_{j=1}^{N_a} m_{ij} a_{k,j} c_{\max,j}$$

where

$$s_{k,i} = \max \left(0, v_{\max,i} - v_{k,i} - p_{k,i} - \sum_{j=1}^{N_a} m_{ij} a_{k,j} c_{\max,j} \right)$$

In a later workshop where the emphasis will be on the effects of system dynamics a proper rainfall-runoff model and a full hydrodynamic model of the sewer system will be used.

4.4 The implementation of the controller

The controller functions as follows. At the design stage a curve $f_k(x)$ is established for each subcatchment that relates the fraction of storage x used in the entire system to the desired fraction of storage f_k used in the particular catchment. In the current version of Composer these curves are of the following form

$$f_k(x) = x^{\beta_k} d(x)$$

where β_k is positive real number and

$$d(x) = \frac{x \sum_{i=1}^{N_V-1} v_{\max,i}}{\sum_{i=1}^{N_V-1} (x^{\beta_i} v_{\max,i})}$$

For $0 \leq x \leq 1$ we have $0 \leq x^{\beta_k} \leq 1$ and $f_k(x) \geq 0$ and

$$\sum_{i=1}^{N_V-1} f_i(x) v_{\max,i} = x \sum_{i=1}^{N_V-1} v_{\max,i}$$

The mass conservation correction $d(x)$ may seem to create a problem: if we try to keep a large subcatchment empty, this may force $f_i(x)$ for another subcatchment to be larger than one. However, this provides clear feedback to the person setting the β_k that his strategy may lead to a forced CSO event. This may in fact be part of the strategy when, at the CSO location, the system in question is known to contain mostly clean rain water as is the case in improved separated systems. Choice of the control parameters is an iterative process that starts with a large number of runs of a simple model with the controller on default settings ($\beta_k = 1$) followed by a manual analysis of events that are of special interest because they are close to what the system can theoretically process without CSO or because a CSO at a certain location could in theory have been prevented.

The simplest such curve results in a controller that tries to distribute the sewage waiting to be pumped to the WWTP equally over the system. When the controller is run (every five minutes or more frequently) it first solves the constrained least squares problem given below

$$\min_{x_{k+1,j} \in [0, c_{\max,j}]} \sum_{i=1}^{N_V-1} \left(v_{k,i} + \sum_{j=1}^{N_a} m_{ij} x_j - f_i(y) v_{\max,i} \right)^2$$

where

$$y = \frac{\sum_{i=1}^{N_V-1} v_{k,i}}{\sum_{i=1}^{N_V-1} v_{\max,i}}$$

and there may be an additional constraint of the form

$$\sum_{j=1}^{N_a} m_{N_V} x_j c_{\max,j} \leq c_{\max, WWTP}$$

imposed by the maximum intake capacity of the WWTP. Next it translates this into actual pump settings (on or off). In the case of the pilot the translation is simple, the pump is switched on when $x_{k,j} = c_{\max,j}$ (the optimization routine reports back $c_{\max,j}$ when the upper constraint on x_j is activated) and the last change in pump status was more than a given time interval Δt_j in the past. Composer has a much more extensive algorithm for this purpose, but for the case of a simple one pump pumping station with a on/off pump this is sufficient.

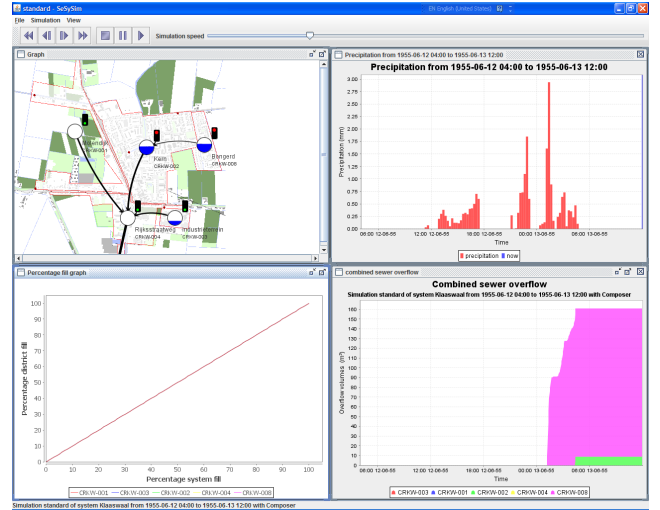


Fig. 2. Simulation results for equal filling

4.5 The software used

The simulator used in the workshop was purpose built to link Composer to a simple reservoir model. For the user interface the package JUNG (2010) was used to visualize the sewer system and the package jfreechart (2010) to provide charts of precipitation and flow. An earlier example of the use of a demonstrator program with a different approach to the user interface and more attention for the details of WWTP operation is described in Messmer et al. (2008).

The user interface consists of one Multi Document Interface per simulation run. The interface displays the simulation controls (step forward, step backward, fast forward, rewind and run), a graph of the sewer system and optionally a graph of the precipitation, graphs of the inflow and outflow per subcatchment, cumulative CSO and so on. The graph of the sewer system contains several visual cues related to the operation of the system. The nodes, displayed as circles, filled with blue as the storage in a subcatchment was used, arcs changed gray shade to indicate pump settings and traffic light icons indicated subcatchment status. The traffic light is green when there is no problem, yellow when in system storage is nearly exhausted and red if at some point during this run a CSO occurred. The width of the arcs indicated the pump capacity relative to the other arcs. A screen shot of the user interface is shown in Fig. 2 and 3.

The pilot system was a simplified version of the sewer system of Klaaswaal, part of the municipality of Cromstrijen. It has five subcatchments: Bongerd, Kern, Rijkstraatweg, Molendijk en Industriegebied, linked as shown in the upper left part of Fig. 2. The line running from Rijkstraatweg off the map represents the pipe line to the WWTP. The user interface for adjustments to the control parameters β_k is shown in Fig. 3.

The participants used all available charting options in combination with the controls that allowed them to run the system forward and backward in time in their examination of the behavior of the system with a local controller and with Composer. The final shared activity was the use of the parameter tuning module to illustrate the flexibility of

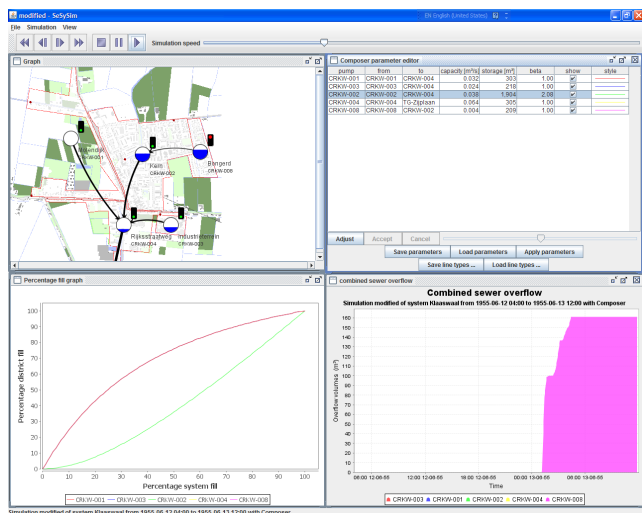


Fig. 3. Fill Subcatchment Kern slowly (green line)

central control. During the hands-on sessions lively debate ensued about the system behavior.

4.6 Examples used

The first example was intended to familiarize the participants with the interface of the software and to demonstrate the link between the simulation and current practice. In this case the system was made to fail by letting the pumps switch on at relatively high water levels in the system. Participants were encouraged to use the software to determine the cause of the problem and to try to remedy the situation through correction of the controller parameters.

In the second example a precipitation event was selected that caused a CSO in a subcatchment that could not cope with both its own load and the pumped upstream inflow. Participants ran this example both with local and with central control. In this case central control could solve the problem by making better use of the available storage in the upstream subcatchment.

In the third example an event was selected where simple central control failed to prevent a CSO at a vulnerable location because it did not take into account differences in excess storage. Participants were allowed to manipulate the parameters of the central controller to take these differences into account and so avoid that particular CSO. As can be seen by comparing Fig. 2 and Fig. 3 with $\beta_{Kern} = 2.09$ and $\beta_j = 1$ in all other subcatchments we can avoid a CSO in subcatchment Kern.

The examples were selected using techniques described in van Nooijen et al. (2010).

5. LESSONS LEARNED

At the trial session before the workshop the sewer system was shown as a graph with subcatchments as nodes and connections between the subcatchments shown as arcs. Based on feedback received, it was decided to put this graph onto a map of the municipality with the nodes at the geographical centers of the sewer subcatchments. It was also decided to add a menu item to load the settings for a run (system, precipitation, controller type and controller

settings) as a group. After the trial session a user interface in Dutch that used the correct Dutch technical terms was implemented. Displayed quantities and units were adapted to Dutch operational sewer management.

Both during the trial session and the workshop it was clear that the distance between simulation and daily experience should be minimized. According to those present during both sessions contributed considerably to the success of the workshop.

The use of the Dutch language and the correct technical terms could be realized with standard software engineering techniques, see for example Dagiene and Laucius (2004). However, the use of quantities and units specific to the field raised an issue that is less commonly addressed. For instance, the available storage in the sewer pipes of a subcatchment is not measured in cubic meters, but in the total number of millimeters of rain falling on the connected surface which is measured in hectares. A complicating factor is the mixing of representations: total pump capacity is in cubic meters per hour. The excess capacity, that is the capacity after subtraction of dwf and inflow from other subcatchments, is often given in millimeter of precipitation on the connected surface per hour.

During the workshop one participant wanted to know whether municipalities would be able to adjust setting in their own system once control at the level of the water board was implemented. We will look into this to see how much room there is for autonomy of separate municipalities to take decisions that directly affect only their own system.

After the workshop it was found that some additional data gathering was needed and therefore it was decided that the second iteration in the control design should be about two calendar months in length with a workshop at the end, followed by a third iteration in the control design of one to two months. It was also decided to concentrate on a simple pilot system. This would allow us to realize the links to Sobek and openMI and development of a suitable user interface without too many additional complications. The system also contained all the technical challenges of the larger systems such as gravity flow connections in addition to pumped connections, possible discrepancies between actual pump status and expected pump status and pumps that have only two states: on or off. Further development of the centralized controller at municipality level and work on a central controller at the level of the water board was tentatively postponed to a later iteration.

Had we not adapted the spirit of agile programming, the DUT team would probably have followed another path where development of the controller took precedence.

6. CONCLUSIONS

We described the context of a project intended to develop an automated central controller. We gave some technical background on the control problem. We then discussed a workshop in this project intended to familiarize the participants from the municipalities and the water board with automatic control and presented them with a possible

approach in the context of a simple simulation. Based on this workshop we drew the following conclusions.

The materials used in a workshop should be in the language of the stakeholders. Any software used should provide a clear visual representation of system state that is directly related to a map of the area. The materials should use the technical terms and the units of measurement to which the participants are used. This implies that reuse of software in other projects or for other stakeholders is possible only if internationalization (i18n in software parlance) is taken very seriously. Note that this may mean that different stakeholder communities may need to be considered as different regions. Finally, we found that the feedback provided by the workshop turned out to be instrumental in deciding on a length and direction for the next iteration of the controller design.

ACKNOWLEDGEMENTS

We wish to thank Deltares for the organization of the workshop. We wish to thank all participants for their enthusiastic participation. The workshop was organized as part of the project “Integrale Sturing Afvalwaterketen en watersysteem Hoeksche Waard” for which SenterNovem provided a subsidy from the “Innovatieprogramma Kaderrichtlijn Water” of the Dutch Ministry of Transport, Public Works and Water Management. The partners in this project are the municipalities Binnenmaas, Cromstrijen, Korendijk, Oud Beijerland en Strijen, The Dutch research institute Deltares, Delft University of Technology and the water board Hollandse Delta.

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