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CONSTRAINT PROGRAMMING FOR OPTIMAL DESIGN OF ARCHITECTURES FOR WATER DISTRIBUTION TANKS AND RESERVOIRS: A CASE STUDY

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A water distribution system is an essential component of any urban infrastructure system. Its design is commonly a hard task mainly due to the presence of several complex interrelated parameters. Among others, some parameters to study are the water demand, pressure requirements, topography, location of resources, system reliability, and energy uses. In this paper, we focus on a real case of water distribution system in order to minimize installation costs by satisfying the given system requirements. We solve the problem by using state-of-the-art Constraint Programming techniques combined with Interval Analysis for rigorously handling continuous decision variables. Experimental results demonstrate the feasibility of the proposed approach, where the global optimum is reached in all instances and in reasonable runtime.

Keywords: *constraint programming, optimization, water distribution*

Programiranje ograničenja za optimalni projekt arhitekture spremišta i rezervoara za distribuciju vode: analiza slučaja

Izvorni znanstveni članak

Sustav za raspodjelu vode je bitna komponenta svakog gradskog infrastrukturnog sustava. Njegov je projekt uglavnom težak zadatak zbog postojanja nekoliko složenih međusobno povezanih parametara. Između ostalih, neki parametri koji se moraju proučiti su potražnja za vodom, potrebni tlak, topografija, lokacija resursa, pouzdanost sustava, i korištenje energije. U ovom smo radu usmjereni na postojeći slučaj sustava za distribuciju vode s ciljem smanjenja troškova instaliranja zadovoljavanjem zahtjeva toga sustava. Problem rješavamo primjenom najnovijih metoda Programiranja Ograničenja kombiniranih s Analizom Intervala u svrhu preciznog baratanja s trajnim varijablama odluka. Eksperimentalni rezultati pokazuju da je predloženi pristup izvediv i globalni optimum postignut u svim slučajevima i u zadovoljavajućem vremenu.

Ključne riječi: *optimizacija, programiranje ograničenja, raspodjela vode*

1 Introduction

A water distribution system is an essential component of an urban infrastructure system. Its construction demands a huge investment and an efficient architecture design is always a major aim of any supply water agency. Important design parameters that are inherently interrelated make the problem complex and tedious to solve. Among others, some parameters to study are the water demand, minimum pressure requirements, topography, location of resources, system reliability, energy uses, as well as pipe, pumps, and reservoir costs and locations. In Chile, water is a scarce resource and represents a big concern. Several natural reservoirs and rivers are dried causing serious consequences. Every year, different regions remain without water. Electricity providers have to lower voltage to fulfil the demand. Various fruits and vegetable plantations are dead and several forests are fired due to dryness. Additionally, after the 27F Earthquake and Tsunami, several components of the water distribution network resulted damaged increasing even more the consequences.

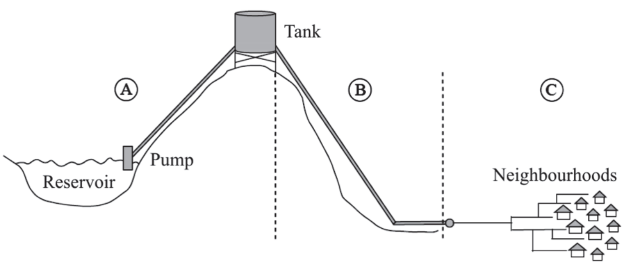

Figure 1 Three-zone architecture

A complete system for water distribution can be seen as the three-zone architecture (see Fig. 1). On the zone A, the water is carried from the reservoir to the tank, on the middle zone the water is conducted from tanks to the main distribution point, and finally on zone C, the water is distributed through a network system to the different neighbourhoods. Numerous works have been reported in the literature for optimal design and cost minimization of zone C. However, no evidence exists for optimal design in zone A and B. In this paper, we focus on the design of optimal architectures for water distribution tanks and reservoirs. The goal is to minimize installation costs related to pumps, tanks, and pipes by satisfying several system constraints. To this end, we model the architecture as a constraint-based optimization problem to be solved with uninvestigated techniques in the context of water distribution, namely Constraint Programming (CP) and Interval Analysis. This is a complex and real-world problem proposed by ESVAL -one of the biggest water distribution agencies in Chile- that requires to investigate several aspects such as the nonlinear relationship between flow and head loss, the presence of discrete decision variables related to pipe diameter and cost functions, as well as the need for continuous domains to represent geographical layouts, multiple flow demand, and location of the architecture components.

This paper is organized as follows: Section 2 presents the related work. The problem is described and modeled in Section 3. Section 4 gives an overview of CP and Interval Analysis. Experimental results are presented and discussed in Section 5. Finally, we conclude and we give some directions for future work.

2 Related work

As previously mentioned, most of research work has been devoted to zone C. The goal of this problem is to find a combination of commercial pipe diameters that minimize the total cost of the network. In this context, preliminary works have been reported on the mid 1960's, where models including continuous diameters [22, 9] and split pipes [26, 23] were in general proposed. Some drawbacks of those models are the conversion of continuous diameter to the nearest commercial size and the use of split pipes. Conversion does not guarantee the true optimal solution, while split pipes are not commonly used in practice. During the last two decades, evolutionary computing has been strongly used to solve water distribution problems [31, 32, 17, 30]. Metaheuristics [7] explore the search space in less computational time compared to a complete technique, however, the global optimum is not guaranteed. Different authors propose to optimize the cost of the distribution networks by using genetic algorithms [8, 11, 29], simulating annealing [6], particle swarm optimization [28, 15, 16], differential evolution algorithms [27, 25], memetic algorithms [1], and ant colony optimization [21]. Constraint logic programming has also been used to solve hydraulic problems [4], indeed for the optimal placement of valves in water distribution networks. However, this problem is quite different to the one tackled in this paper.

In this paper, we focus on a case study devoted to zones A and B, which in contrast to the well-studied problem of zone C, also considers the minimization of tanks and pumps costs. This makes the problem more realistic since both components have a considerable impact on the operation and installation investment. We solve the problem with unexplored techniques in the context of water distribution, namely CP and Interval Analysis for rigorously handling continuous decision variables. This combination, as opposed to metaheuristics, guarantees the global optimum of the problem.

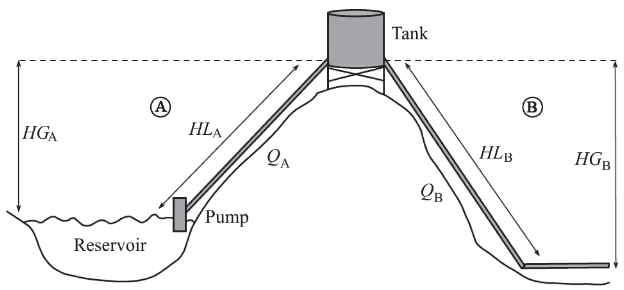

Figure 2 Zones A and B of the water distribution system

3 Problem statement

As previously noted, we focus on zones A and B of the water distribution system. Fig. 2 depicts a schema illustrating a common layout of zone A and B. On the zone A, HG_A denotes the height from the reservoir to the tank, HL_A is the pressure loss from reservoir to tank that must be handled by the pump, and Q_A corresponds to the flow necessary to guarantee the tank supply. On the zone B, HG_B denotes the height from the tank to the main distribution point, HL_B is the pressure gained due to gravity, and Q_B corresponds to the flow needed to fulfil the demand of population[1]. The complete set of variables as well as constraints and the objective function are outlined in the following.

3.1 Objective function

The goal of the problem modelled and solved herein is to minimize the total capital costs, considering pipes, tanks, and pumps. This can be expressed as follows and decomposed in Eqs. (2), (3), and (4).

3.2 Minimize

$$COST_{\text{pipes}} + COST_{\text{tanks}} + COST_{\text{pumps}}, \tag{1}$$

$$COST_{\text{pipes}} = \sum_{i=1}^{n_\text{p}} c(D_i)L_i, \tag{2}$$

where n_p is the number of pipes, $c(D_i)$ is the cost per unit length of the i^{th} link ($/m) with diameter D_i (mm), and L_i is the length of the i^{th} link (m).

Table 1 Pipe costs in US Dollars per meter of the length

Type	Diameter / mm	Pipe cost / $/m	Installation cost / $/m	Total cost / $/m
PVC-1075	75	6,47	12,53	19
PVC-10110	110	11,91	13,5	25,41
PVC-10140	140	18,32	14,34	32,66
PVC-10200	200	30,66	16,11	46,77
PVC-10315	315	60,2	19,74	79,94
PVC-10400	400	95,3	22,64	117,94
HDPE-1075	75	8,85	12,53	21,38
HDPE-10110	110	15,1	13,5	28,6
HDPE-10140	140	20,9	14,34	35,24
HDPE-10200	200	36,69	16,11	52,8
HDPE-10315	315	75,52	19,74	95,26
HDPE-10400	400	119,4	22,64	142,04
HDPE-101000	1000	771,13	57,73	828,86
STEEL75	76	46,74	12,56	59,3
STEEL110	110	53,11	13,27	66,38
STEEL160	160	77,12	14,69	91,81
STEEL200	200	96,51	16,2	112,71
STEEL315	315	139,36	19,84	159,2
STEEL400	400	177,18	23,37	200,55
STEEL1000	1000	405,47	58,71	464,18

Table 2 Pump costs in US Dollars

Volume / m^3	Cost
150	104 234
350	185 005
400	207 596
750	315 826
1000	383 096
1500	505 790
2000	639 229
3000	889 117
4000	1 141 530
5000	1 434 765
7000	1 906 025

[1] Let us note that Fig. 2 corresponds to a basic diagram for reference, a real scenario may include more than one tank, pump, and several pipe links.

Table 3 Tank costs in US Dollars

Volume / m^3	Cost
150	104 234
350	185 005
400	207 596
750	315 826
1000	383 096

$$COST_{\text{tanks}} = \sum_{j=1}^{n_t} c(V_j), \tag{3}$$

where n_t is the number of tanks, $c(V_j)$ is the cost of the j^{th} tank with volume V_j (m^3).

$$COST_{\text{pumps}} = \sum_{k=1}^{n_{pu}} c(P_k), \tag{4}$$

where n_{pu} is the number of pumps, $c(P_k)$ is the cost of the k^{th} pump with power P_k (HP). An overview of costs is given in Tabs. 1, 2 and 3 for reference.

3.3 Constraints

The problem is subjected to several system constraints related to population demand, pipe types, tank and neighbourhood location, pressure and pressure loss coefficients, fire and back-up water volumes, among others. For instance, the selected pumps must be able to reach the tank considering the pressure loss due to the gravity force. This is computed by Eqs. (5) and (6).

$$HG \leq HP - HL, \tag{5}$$

where HG is the height from point x to y (m), HL corresponds to the hydraulic head loss/gained (m), and HP is the pump pressure required (m). The necessary pump power is calculated as follows.

$$P_k = Q_i \times HP \times e, \tag{6}$$

where Q_i is the flow at pipe i (l/s), and e is a coefficient in percentage that defines the pump efficiency. The head loss for pipe i is calculated via the Hanzen-Williams equation[2] as shown below.

$$HL_i = \frac{\alpha \times L_i \times Q_i^{1,85}}{C_{\text{HW}}^{1,85} \times D_i^{4,87}}, \tag{7}$$

where L_i is the length of the pipe i, Q_i is the pipe flow, C_{HW} is the Hanzen-Williams coefficient, D_i the diameter of the pipe i, and α is the conversion factor which depends on the unit used for computation (in this case, α = 10,667). The demand at zone A and B are calculated conformed to the Chilean Regulation NCh691.Of98 [18] by Eqs. (8), (9), and (10).

$$Q_{\text{A}} = FDMC \times Q_{\bar{x}}, \tag{8}$$

$$Q_{\text{B}} = FHMC \times Q_{\text{A}}, \tag{9}$$

$$Q_{\bar{x}} = \frac{N \times Prod \times Cov}{\beta \times (1 - Q_{\text{loss}})}, \tag{10}$$

where FDMC and FHMC are statistical factors given by the maximum consumption day and maximum consumption hour, respectively. $Q_{\bar{x}}$ is the average daily flow (l/s), N is the population, $Prod$ is the annual production per person per day (litres/person/day), Cov is the annual coverage in percentage, β is another conversion factor (in this case to transform days in seconds, β = 86 400), and Q_{loss} is the loss flow. Now, the following constraints are also given by the Chilean Regulation NCh691.Of98. For instance, flow at zone B is bounded by a mandatory minimum and maximum.

$$15 \leq Q_{\text{B}} \leq 70. \tag{11}$$

The tank volume must be computed as illustrated in Eq. (12).

$$V_j = \max\left[V_{\text{reg}} + V_{\text{fire}}, V_{\text{reg}} + V_{\text{bu}}\right], \tag{12}$$

where V_{reg} is the volume of regulation, which corresponds to 15 % of 24 hours of Q_{A}. V_{fire} is the volume set for fire, which depends on the population and fireplugs as shown in Tab. 4. Finally, V_{bu} is the volume given for back-up, which corresponds to 2 hours of Q_{A}.

Table 4 Fire Volume

$N(\times 1000)$	Number of fireplugs simultaneously used	V_{fire} / m^3
≤ 6	1	115
$6 \leq N \leq 25$	2	230
$25 \leq N \leq 60$	3	346
$60 \leq N \leq 150$	5	576
≥ 150	6	690

4 Numerical constraint satisfaction problems

4.1 Definitions

A Constraint Satisfaction Problem (CSP) is a formal problem representation, which mainly consists of a sequence of variables holding a domain and a set of relations over those variables called constraints. The idea is to find values for those variables so as to satisfy the constraints. The software technology devoted to tackle this problem is named Constraint Programming. In this work, due to the presence of continuous decision variables, we focus on Numerical CSP (NCSP), which is an extension of a CSP devoted to continuous domains. Formally, a NCSP P is defined by a triplet $P = \langle X, [x], C\rangle$ where:

- X is a finite sequence of variables $X = \langle x_1, x_2, ..., x_n\rangle$.
- $[x]$ is a finite set of real intervals $[x] = \langle [x_1], [x_2], ..., [x_n]\rangle$, such that $[x_i]$ is the domain of x_i.

[2] The Hanzen-Williams equation is the most common head loss equation used in research papers and in particular in ESVAL.

- C is a finite set of constraints $C = \langle c_1, c_2, ..., c_n \rangle$.

A solution to a NCSP is a set of real intervals that satisfy all the constraints. Optimization problems are handled in the same way. Hence, the 4-tuple $P = \langle X, [x], C, f(x) \rangle$ is employed in this case, where $f(x)$ is the cost function to be maximized or minimized.

4.2 NCSP Solving

In order to guarantee accurate solutions, NCSPs cannot be handled in the same way as CSPs mainly due to the presence of constraints over real numbers. Indeed, the representation of reals in numerical computations is not exact since it is commonly done by means of floating-point numbers, which are a finite set of rational numbers. This inaccuracy may lead to rounding errors and as a consequence to reaching wrong solutions. One solution for rigorously dealing with real numbers relies on the integration of interval analysis on the solving process. The idea is to compute approximations over domains represented by intervals bounded by floating-point numbers [3, 19]. A detailed presentation of interval analysis can be seen in [10].

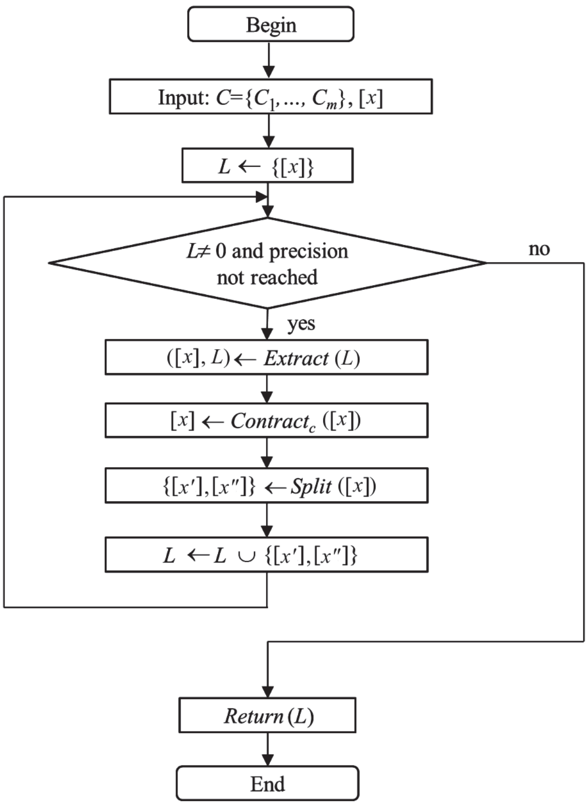

Figure 3 A branch and prune algorithm for NCSPs

Then, the core idea for solving NCSPs relies in combining a branch and prune algorithm with interval analysis for handling continuous domains. A tree-data structure that holds intervals as the potential solutions is built on the fly by interleaving branching and pruning phases. The branching phase is responsible for creating the branches of the tree by splitting real intervals, while the pruning tries to filter from domain intervals that do not conduce to any feasible solution. The idea is to speed-up the solving process. This is possible by applying consistency techniques for continuous domains such as the hull and the box consistency [12, 2], which are similar to the arc-consistency [13] for finite domain CSPs.

Fig. 3 depicts an algorithm for rigorously handling NCSPs. The procedure begins by receiving as input the set of constraints and domains of the problem. Then, four actions are embedded in a while loop. The *Contract* operator is responsible for pruning the tree, and *Split* applies a dichotomic division of intervals in order to carry out the branching process. Every computation of elementary operations $\{+, -, \times, /\}$ is done by using interval arithmetic. The process stops when the real values of the solution have reached the precision required of the problem.

4.3 A Branch and Bound Algorithm for NCSPs

A slight modification to the previous algorithm is required to handle optimization problems. Indeed, here a CP-based branch and bound algorithm is combined with interval analysis (see Fig. 4).

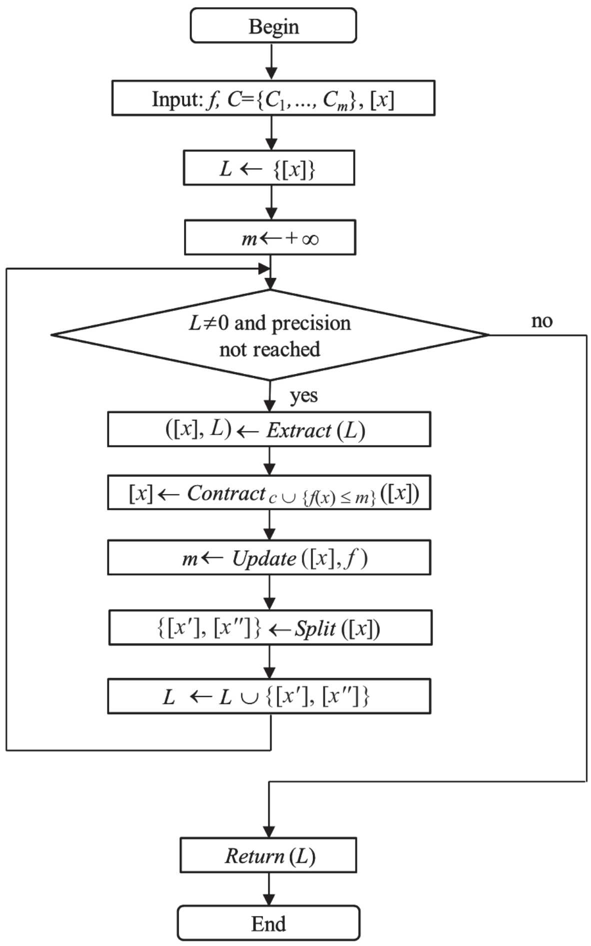

Figure 4 A branch and bound algorithm for NCSPs

The corresponding cost function f has been added to the input set. A variable m is initialized to $+\infty$ in order to maintain an upper bound on the global minimum. In this way, potential solutions exceeding this bound are discarded by adding $f(x) \leq m$ to the set of constraints. Five instructions are embedded in the same while loop.

Now, *Contract* takes into account the cost function in order to prune the tree. The *Update* function has been added for updating the upper bound once better solutions are found. The branch and bound algorithm implemented in the Eclipse CP System [33] has been used to tackle the water distribution problem, which basically proceeds as Algorithm 2 does.

5 Experiments

We have performed a set of experiments in order to assess the efficiency of the proposed implementation. We have designed and launched the model for optimal design of architectures for water distribution tanks and reservoirs considering data from different scenarios. We have tested 110 instances (available in [20]) on a 3.06GHz Intel Core 2 Duo with 2Gb RAM running Ubuntu Linux.

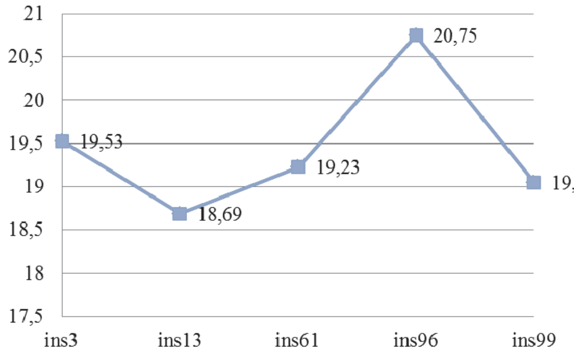

Figure 5 Five worst solving times

All instances consider the same variables and the following constants according to the provided data: *FDMC*: 1,2; *FHMC*: 0,3; $\alpha = 10{,}667$; $\beta = 86400$; $Cov = 1$; $Q_{loss} = 0{,}4$; $FC = 1$; $e = 0{,}6$. Then, two main constants vary depending on the location of the distribution system: the population (N) and the height difference between positions of zone A and B (δ_h). Tab. 5 illustrates the population and the δ_h value for all instances. Let us note that the global optimum was reached for all tested instances. This is guaranteed by the Eclipse CP system, since the algorithm used explores the whole search space.

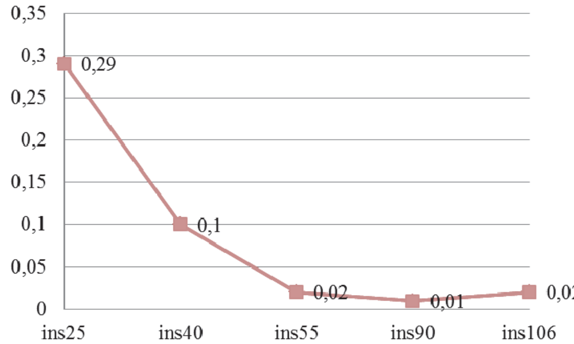

Figure 6 Five best solving times

Now, considering solving times, we have selected the five worst and the five best instances (see Figs. 5 and 6). Regarding these results, it turns out that no clear relation exists between the size of N and δ_h w.r.t. solving times. Indeed, worse times are produced by instances that require a strong computation to calculate large amount of decimals for floating-point numbers, in particular when the Hanzen-Williams equation is processed. However, we believe that solving times are reasonable: the slowest instance does not exceed 21 seconds, while the fastest one requires 10^{-2} seconds to be solved.

Table 5 Tested instances (N − population, δ_h − height difference between zone A and B)

	N	δ_h		N	δ_h		N	δ_h		N	δ_h		N	δ_h
ins1	7,3	26,6	ins23	7,8	43	ins45	10,1	28,7	ins67	12,3	41,3	ins89	15,3	34,8
ins2	7,3	28,7	ins24	7,8	45,1	ins46	10,1	31,4	ins68	12,3	43	ins90	15,3	35,3
ins3	7,3	31,4	ins25	7,8	47,4	ins47	10,1	32,5	ins69	12,3	45,1	ins91	15,3	37,6
ins4	7,3	32,5	ins26	7,8	50,9	ins48	10,1	34,8	ins70	12,3	47,4	ins92	15,3	40
ins5	7,3	34,8	ins27	7,8	51,3	ins49	10,1	35,3	ins71	12,3	50,9	ins93	15,3	41,3
ins6	7,3	35,3	ins28	7,8	54,8	ins50	10,1	37,6	ins72	12,3	51,3	ins94	15,3	43
ins7	7,3	37,6	ins29	8,2	26,6	ins51	10,1	40	ins73	14,5	26,6	ins95	15,3	45,1
ins8	7,3	40	ins30	8,2	28,7	ins52	10,1	41,3	ins74	14,5	28,7	ins96	15,3	47,4
ins9	7,3	41,3	ins31	8,2	31,4	ins53	10,1	43	ins75	14,5	31,4	ins97	18,1	26,6
ins10	7,3	43	ins32	8,2	32,5	ins54	10,1	45,1	ins76	14,5	32,5	ins98	18,1	28,7
ins11	7,3	45,1	ins33	8,2	34,8	ins55	10,1	47,4	ins77	14,5	34,8	ins99	18,1	31,4
ins12	7,3	47,4	ins34	8,2	35,3	ins56	10,1	50,9	ins78	14,5	35,3	ins100	18,1	32,5
ins13	7,3	50,9	ins35	8,2	37,6	ins57	10,1	51,3	ins79	14,5	37,6	ins101	18,1	34,8
ins14	7,8	26,6	ins36	8,2	40	ins58	10,1	54,8	ins80	14,5	40	ins102	18,1	35,3
ins15	7,8	28,7	ins37	8,2	41,3	ins59	12,3	26,6	ins81	14,5	41,3	ins103	18,1	37,6
ins16	7,8	31,4	ins38	8,2	43	ins60	12,3	28,7	ins82	14,5	43	ins104	18,1	40
ins17	7,8	32,5	ins39	8,2	45,1	ins61	12,3	31,4	ins83	14,5	45,1	ins105	20	26,6
ins18	7,8	34,8	Ins40	8,2	47,4	ins62	12,3	32,5	ins84	14,5	47,4	ins106	20	28,7
ins19	7,8	35,3	Ins41	8,2	50,9	ins63	12,3	34,8	ins85	15,3	26,6	ins107	20	31,4
ins20	7,8	37,6	Ins42	8,2	51,3	ins64	12,3	35,3	ins86	15,3	28,7	ins108	20	32,5
ins21	7,8	40	Ins43	8,2	54,8	ins65	12,3	37,6	ins87	15,3	31,4	ins109	20	34,8
ins22	7,8	41,3	Ins44	10,1	26,6	ins66	12,3	40	ins88	15,3	32,5	ins110	20	35,3

6 Conclusions

In this paper, we have modelled and solved a real case of architectural design for water distribution tanks and reservoirs. We have employed state-of-the-art constraint programming technology combined with interval analysis in order to rigorously handling continuous domains. We have performed a set of experiments by using instances generated from real scenarios. The obtained results demonstrated the feasibility of the proposed approach; indeed, the global optimum was reached in all instances and in reasonable runtime. An interesting extension of this work would be related to the use of Autonomous Search in conjunction with constraint programming. As noted in [6, 13], this combination can accelerate the resolution process, especially in harder instances.

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