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Modeling Results : Case Study of Belo Horizonte
Optimising Sewer System Rehabilitation Strategies
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MAIN AUTHOR: Eng. M.Sc. Wilmer Barreto

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CO	Confidential, only for members of the consortium (including the Commission Services)	

SWITCH Deliverable Briefing Note Template

SWITCH Document
Deliverable D1.2.11
Modeling Results : Case Study of Belo Horizonte

Audience

The document was prepared for an audience both inside and outside the SWITCH consortium. For consortium members it gives an overview on how the optimization techniques by using multi-objective genetic algorithm can be used together with an urban drainage computational engine to solve urban flooding. It also demonstrates the potential to use this optimization technique in complex urban drainage networks that can take a considerable amount of computation resources and time, by using parallel computation and clusters. External audience consists of mainly academic fellows that are currently working on similar subjects.

Purpose

The purpose of the document is to review the progress in the implementation of optimization of sewer system rehabilitation strategies to solve urban flooding.

Background

This document contributes to the SWITCH approach proposed during the project. The document is a step towards the development of a set of tools to evaluate city's sustainability and future scenarios of development.

Potential Impact

The document presents the results of the on-going research work that aim to contribute to the development of a new approach for urban drainage infrastructure planning and design which help water companies and municipalities to improve the effectiveness of their investments and contributes to the sustainability of the systems.

Issues

Not applicable

Recommendations

The document consists of a description of the application of a new optimization approach for urban drainage networks applied in the city of Belo Horizonte.

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Optimising Sewer System Rehabilitation Strategies

Summary

Sewer systems constitute a very significant portion of all assets in urban areas. Their structural integrity and functional efficiency represent key parameters for the safe transfer and disposal of surface run-off and domestic/trade discharges. The failure of these assets may easily result in uncontrollable discharges and surface flooding, pollution of receiving waters, pollution of ground water and soil, treatment plant impacts and increasing maintenance costs. The lack of an appropriate methodology for remedial works identification may result in expenditure programmes not achieving their given objectives, and therefore, the optimisation of rehabilitation works is of utmost importance. A platform that links the hydrodynamic model of a drainage system with the multi-criteria global evolutionary optimisation engine that takes into account the performance indicators relevant for rehabilitation decisions (including various constraints such as, system capacity, overflow emissions, and investment costs) related to the system's operation is being developed. The results obtained to date suggest that the proposed approach can be effective in solving some of the difficult problems concerning urban drainage/sewerage infrastructure.

1. Introduction

Sewer systems constitute a very significant portion of all assets in urban areas. Their structural integrity and functional efficiency represent key parameters for the safe transfer and disposal of surface run-off and domestic/trade discharges. The failure of these assets, which could be caused by various factors such as ageing, structural collapses, inflow/infiltration, exfiltration (leaking) and insufficient capacity due to increased urbanisation, may easily result in uncontrollable discharges and surface flooding, pollution of receiving waters, pollution of ground water and soil, treatment plant impacts and increasing maintenance costs. Therefore, the sustainability of such assets, which frequently, if not continuously, interact with other components of urban water cycle (i.e., water supply, groundwater and receiving waters), is therefore an important issue for urban drainage system managers. Furthermore, the frequency of high intensity rainfall seems to increase in many regions and climatologists predict climate changes that will increase the problem even further.

The lack of an appropriate methodology for remedial works identification may result in expenditure programmes not achieving their given objectives, and therefore, the optimisation of rehabilitation works is of outmost importance. With the reference to the work published to date, the practitioner's attention to the use of full-fledge multi-criteria global evolutionary optimisation techniques in the dynamic context of sewer systems is found to be very limited.

A platform that links the hydrodynamic model of a drainage system, MOUSE by DHI, with the multi-criteria global evolutionary optimisation engine, NSGA II developed by Deb, 2002, which takes into account the performance indicators relevant for rehabilitation decisions (including various constraints such as, system capacity, overflow emissions, flooding, and investment costs) related to the system's operation is being developed.

The advantage of this approach over the standard industry applied approaches (which are often limited to the use of a linear optimization scheme or a non-hydrodynamic computation) is that it solves the problem within the entire catchment with the use of sophisticated optimisation techniques and takes into account the dynamic nature of drainage systems during the process of identifying the least cost rehabilitation option.

Moreover, one of the main problems to face in urban drainage systems optimization is the computational time. Solving the hydrodynamic equations in order to estimate water depth, velocity and flood duration can be a bottleneck in the optimization process. It becomes worse if a dual modeling (using 1D and 2D-hydrodynamics model) is used inside of the optimization process. There are three main approaches to accelerate the computation process and improve the performance, one is to use a faster machine, other to improve the algorithm and the other is to divide the whole process in smaller task and use several computer or processors.

After some analysis of the above mentioned options was realized that the most suitable was the use of several personal computers (PCs) or processors. In the optimization process of a sewer network the most consuming task is the evaluation of the objectives function. As it was mentioned, the use of hydrodynamic models require of high computation load. To improve it through the use of software requires having access to the source code and the most robust software are commercial and no open source. The use of better and faster machines is a good option, however, now a days the PCs is reaching it physical speed limits with current technology. Moore's law (1965) state that speed of the computer increase exponential in time, due to the use of smaller and faster transistors it was true in the last 40 years but miniaturization of the transistors is reaching the limit of the atoms and it is necessary a different technology to gain in CPU speed, nano-technology is promising in this aspects but not enough mature. Not only the CPU speed is a problem, also bandwidth and memory can become a bottleneck. For such a reason, CPU and computer manufacturers, INTEL and AMD, are moving to multi-processor computers to gain in computation performance.

The best bet now, to gain speed in computation, is the use of multiple processor or the use of multiple computers. However it is not a straightforward approach, it requires of techniques in parallel programming. The most suitable approach is the parallelization of function evaluation in the multi-objective evolutionary algorithm (MOEA). The main goals of parallelizing a MOEA are usually the acceleration of the computation and the gain of quality according to the approximation of the true Pareto front. Also, the diversity of the solutions would be benefited with the use of parallel processing because it is possible to manage larger sets of alternatives than for a single optimization. In order to take a real advantages of parallel computations, the serial algorithm has to be divided in smaller serial tasks, such a tasks must be independent or "quasi- independent" between them in data and execution. It makes possible to execute them in parallel using other processors or PCs.

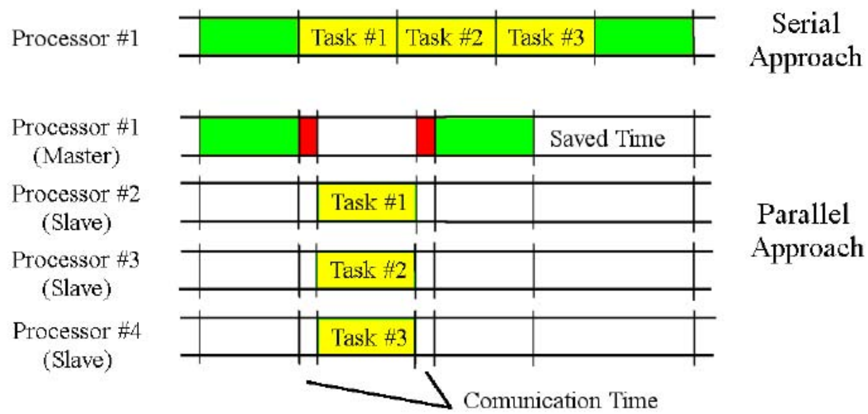

Figure 1: Parallel vs serial computing algorithms

Figure 1 shows an ideal scheme of a serial algorithm parallelization. A serial algorithm is divided in three tasks that are not dependent one each other, and each task is sent to an individual PC or processors, saving in this way valuable execution time. The total execution time is consuming in calculations and communications between PCs or processors.

This document presents the results from an ongoing research work that will be published as the result of the PhD work of Barreto in 2011. It builds upon the foundation of earlier research efforts (Vojinovic et. al. 2006, Barreto et. al. 2007, Vojinovic et. al. 2007).

2. Methodology

The present work explores the use of some of the recent multi-objective evolutionary approaches such as NSGA-II (Deb, 2002) for the purpose of finding optimal sewer system rehabilitation strategies by using three objective functions namely, rehabilitation cost, flood damage and overflow caused pollution.

To handle the optimization process the NSGA-II algorithm developed by Deb (2002) was used. The NSGA-II has been tested and probed to develop good Pareto fronts and can manage several objective functions and constraints (i.e Barreto et al 2006, and Muschalla 2006). The MOUSE by DHI is used as computational engine to simulate hydrologicaland hydraulics routing and processes in the system.

To link the genetic algorithm with the computation engine MOUSE a set of intermediate link routines were written. The first one runs the original model in MOUSE and computes the magnitude of the flooding, the surcharged pipes, and the initial values of the different variables and maximum values of the objective functions. The second routine directly links the NSGA II and MOUSE by interpreting the randomly generated population of the GA for the variables and computing the value of the two objective functions that are passed to the GAs for evaluation and generation of further populations.

The following steps are used in finding the optimal alternative of rehabilitation works requirements (see Figure 2):

- Initial simulation of the existing drainage network.
- Performance evaluation against given standards (constraints).
- Calculation of objective functions.
- Identification of the new drainage network set up (i.e., new rehabilitation strategy).
- Simulation of the new drainage network.
- Pareto Set defined

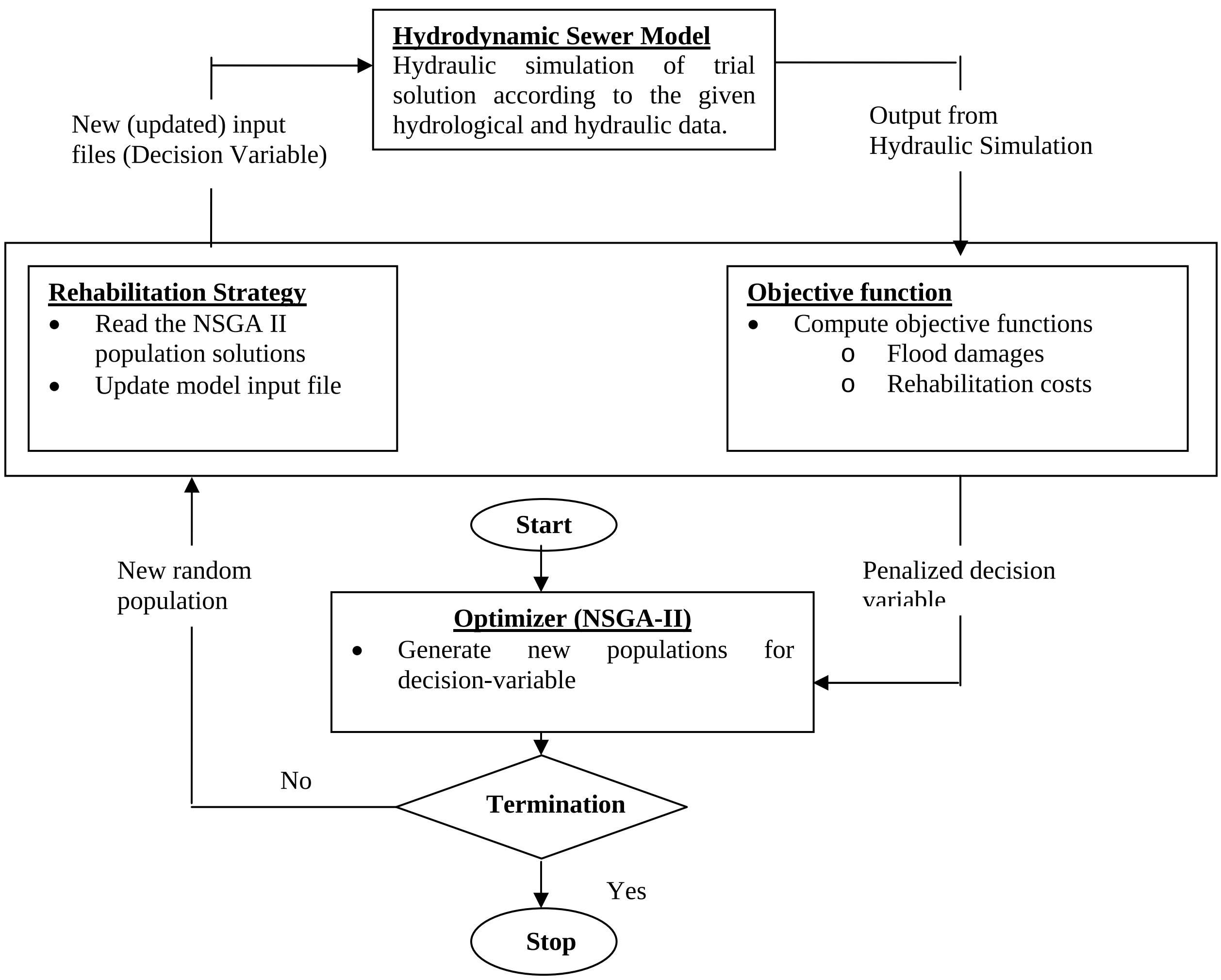

Figure 2. Schematization of the optimization loop.

2.1 The computational Engine

Computation of the objective functions’ values is based on the hydrodynamic simulations of the water motion in a pipe network. For this purpose MOUSE software package (developed by DHI Water and Environment) is used. This modeling system solves the Saint Venant equations (1D) and it was selected due its robustness and the possibility of connecting it with the two-dimensional (2D) modeling system MIKE21 for the surface water simulation.

In addition to the below-ground pipe network system, the above-ground or major system, representing the streets, is simulated with the same 1D model. If the water level at a node reaches the ground level, water flows to the street over a weir with the crest level at the ground level and a crest length equal to the manhole perimeter. Water can flow along the streets and back into the pipe network system or flood other areas when the water level in the street is above the curb level. The above-ground model is complemented with a simplified model for water levels greater than the curbs. In this model excess water at a node fills an inverted cone with a prescribed level-area-volume-cost table constructed for this purpose at each node in the street network.

2.2 The Objective Functions

Two objective functions are evaluated: rehabilitation investment costs and damage cost due to flooding. Investment cost and flood damage can be measured in monetary terms, but it should be note that different stakeholders carry these costs. These two objectives are conflicting: more investment reduces damages and vice-verse. An interface software in the platform was developed in order to compute the objectives. The interface runs the hydrodynamic model, selects the critical pipes for the renewal, computes investment cost and calculates flood damage costs. Finally, it returns control to the optimizer.

Only pipe renewal is considered as a rehabilitation technique; all pipes are cost the same independent of their spatial location; the expenditure is not phased in time and only one design rainfall is considered. These assumptions are made in order to do not complicate the presented methodology by too many details.

2.2.1 Investment Cost

For rehabilitation, only pipe replacement is considered. A table of replacement costs for commercial pipe diameters per unit length is used to calculate the overall costs. These unit costs include: pipe cost, excavation, installation of the pipe per unit length and restoration and reinstatement. For the Case in Belo Horizonte, the pipe network is not a circular pipe system, so the interface program was updated to manage circular, square and rectangular conduits. A new catalog conduit catalog is added for each type of section in the network.

Such costs are normalized using the maximum cost expected for the rehabilitation. The maximum cost is computed assuming that it is necessary to change all the pipes that are allowed to change for the largest diameter from the catalog of pipes. The mathematical expression of the function (f1) for the underground costs can be written as:

$$f_1 = \frac{\sum_{i=1}^{n} C_i \cdot L_i}{\sum_{i=1}^{n} C_i^{max} \cdot L_i}$$

where: L is the pipe length, C is the pipe replacement cost and C_{max} is the maximum pipe cost.

2.2.2 Flood Damages

Flooding damage cost is computed using the following procedure. For each node the maximum spilled volume is determined from the hydraulic model. Using this volume and the pre-prepared table of level-area-volume-cost for each sub-catchment, the level is computed by interpolation. The depth for a single cell is computed by subtracting this level from the ground level given by the topographic raster map.

In order to evaluate the risks to communities, properties and infrastructure effectively, it is important to estimate the distribution of hazards and the magnitudes of flood-related damages. Generally, such damages are divided into tangible and intangible damages. Those damages that can be estimated and expressed directly in monetary terms are the so-called tangible damages (e.g., damages to properties, infrastructure, etc.). Within the scope of this case only this type of damages is considered. There are several variables that can be used for analyzing the tangible damages, the most common are: depth, velocity and duration of flooding. Also, land use is of major importance as it defines the type, cost and vulnerability of structures. There are several equations that can be used to estimate flood damage costs in urban areas (Tang et al 1992). In this paper we use the following relationship:

$$FLD = a + b \cdot DEP + c \cdot DUR$$

where: FLD is the flooding damages per unit area, a, b and c are coefficients related to land use, DEP is the water depth, and DUR is the flooding duration. Flooding duration is also neglected and the value of *a* is assumed to be zero.

However, the value of b is variable: b= fc*Cmax , where fc is a factor dependent on the depth (DEP), and Cmax is the maximum cost damage per unit area. The values are taken from Van der Sande et al (2003) and correspond to studies carried out in The Netherlands on flood damage around the Meuse River. The associated graphs were digitized and located in a file for use with the model integration.

Finally, the equation for flood damages can be expressed as:

$$f_2 = \frac{\sum_{i=1}^{ncells} \sum_{k=1}^{nlu} (fc_i^k \cdot C_{max}^k \cdot DEP_i)}{\sum_{i=1}^{ncells} \sum_{k=1}^{nlu} (fc_i^k \cdot C_{max}^k \cdot DEP_{max})}$$

where: f_2 is the total flood damage, *ncells* is the total number of cells in the raster map, *nlu* is the total number of land use types, fc^i_k is the value of damage factor at i^{th} cell with k^{th} land use type, and DEP_i is the depth at i^{th} cell.

2.3 NSGA II Parallelization

The parallelization of Multi-Objective Evolutionary Algorithm (MOEA) is intended to speed up the optimization process regarding computational time. MOEA can be parallelized in their genetic operands or in the objective function evaluations. The first has been addressed in multiprocessor computers with shared memory, in which the access to the computer resources (memory, buses and CPU) is faster than clusters. The second is used in cluster of computers where more time is consume in communication making not reasonable the parallelization of the genetic operands but make possible the parallelization of the objective functions. In the case of urban drainage optimization, where hydrodynamic models are used to compute the objectives function the second way is preferred. There are three main approaches or paradigms to parallelize MOEA algorithms, they are master-slave, Island, and Diffusion models approaches (Figure 3). There are more classifications but almost all can fit in these three main models. The selection of one model or other depended of the nature of the problem.

In Master-slave models one processor (master) is in charge to send the data to slave processors and collect the results after execution, only communication exist between master and slaves processor. MOEA genetic operators will be done in the master processor and the function evaluations in the slave processors. In the case of the Island model, the MOEA population is divided in sub-populations and a MOEA is running for each sub-population in its own processor, they will converge to different regions of the Pareto front. They share the good genes in order to build the whole Pareto set. The diffusion model deals with one population based in a neighbourhood structure, the genetic operators are applied only between neighbours on the structure, and each individual is assigned to a processor. More detailed information about MOEA parallelization can be found in Coello et al (2002).

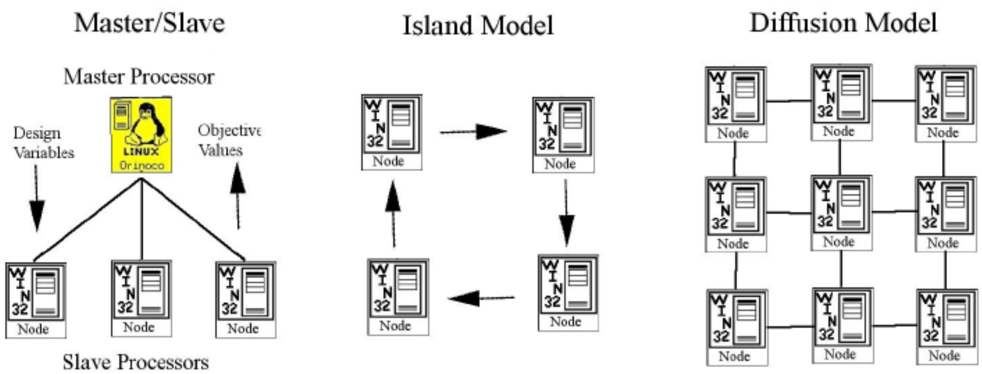

Figure 3. Parallel MOEA paradigms

2.4 The NSGAXp Algorithm

The selected multi-objective evolutionary algorithms selected for parallelization is the NSGA-II. It was selected due to the well-tested robustness to converge to the Pareto front and it has shown a good performance as it was shown in precedent sections and in Barreto et al 2006. The algorithm was parallelized in a "coarse-grained" fashion which more suitable suitable for a Master – Slave model.

The new developed algorithm was called NSGAXp. It was developed in C++ and compiled using GNU g++ and Delphi, taken like base the serial version for windows NSGAX by Barreto and Solomatine. Due to the bottleneck is the hydrodynamic model; the task to be suitable for parallelization is the individual evaluation, in other words the objectives evaluation which involve the running of the hydrodynamic models.

The program is divided in two algorithms, one that will work as master, called NSGAXpm and the other that will perform the objective functions calculations, called NSGAXps. In between there is interface layer composed by an scheduler and parallel library to be used, Figure 4 shows the flowchart schema of parallelization. The importance and design of the scheduler will be treated in a further section.

The master, NSGAXpm, is in charge to control the evolutionary operand, and the following set of instruction to achieve parallelization:

1. Start the slaves nodes: this command will use the daemon (server) to start all the nodes that will conform the parallel virtual machine. These processes can be done also manually, but the user will need physical access to each node making impractical if there is more than 2 nodes.

2. Send a configuration command: The master will indicate to slave to carried a set of predefine instruction that maybe necessary before the function evaluation start. For instance if more that one function evaluation task will be send to same node or processor, the salve has to open independent folders for each tasks in order to avoid result mixing and errors due to be accessing same files.

3. Send individuals for evaluation: It has to send each individual of the population to each task opened as slave (nodes) for evaluation.

4. Apply genetic operators and repeat step 3 until the stopping criteria is met.

5. Send a termination command to each slave in order to free memory, delete temporal folders and files, and close the slave.

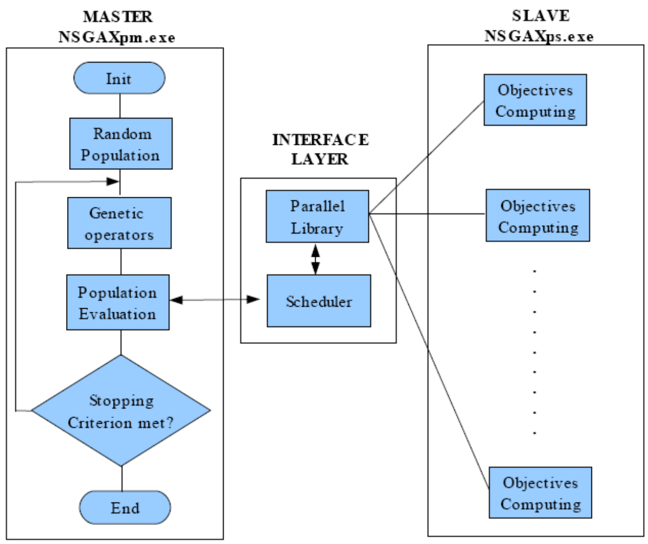

Figure 4. NSGAXp schema

The slave, NSGAXps, accept the following set of instruction from the master:

1. Waiting loop: once it is started the slave, it will wait in a loop for a command from master:
- Configuration: as it was stated this command will execute a set of instruction need before evaluate any individual from the population
- Evaluate individual: if the command is individual evaluation, the slave will start a receiving process. It will receive the design variables to compute the objective functions. This include the running of the hydrodynamic model.
- Termination command: It will end the task on slave computer

2. If the command is different to termination command, the algorithm will return to step one, waiting process.

2.4.1 Network Topology Selection

The structure of cluster to test our parallel implementation was configured like in a normal office network, and it was added to the existing institute network building. This was intentionally done because not always is possible to optimize network connexions at offices and the aim is to carry out the test over a normal configured network. The network configuration issues as network topology, and components for fast computation

(Giga bits networks), which are very important for “fine-grain” cases, are out of scope of this study.

A set of ten old and cheap computers was selected as can be seen in Table 1. It must be highlighted the heterogeneity in brand, speed and operating system of the network. This makes more difficult to estimate the performance, but it represent a common office network configuration. All ethernet card were 10/100 MBps connected with two switch HP 212M at 10/100 MBps. The figure 5 shows the network configuration, topology, OS, function and PC number. Additionally, the main network institution is composed of more that 100 of PCs which increase communication on the network and introduce more noise to the experiments. This main network has a file server and licence server, one issue is that the hydrodynamic model has to check the license over the network, which increase communication time and delay the computation of the objective functions.

Table 1. Network PC nodes configuration

Qt	CPU	RAM KB	OS	Speed MHz
1	AMD Athon (Laptop)	128	Debian LINUX etch	800
4	Intel Celeron (Desktop)	128	Win-2000	1800
4	Intel Celeron (Desktop)	128	Win-2000	2000
1	Intel P4 (Desktop)	256	Win-2000	1800
1	Intel P4 (Desktop)	256	Win-2000	2400

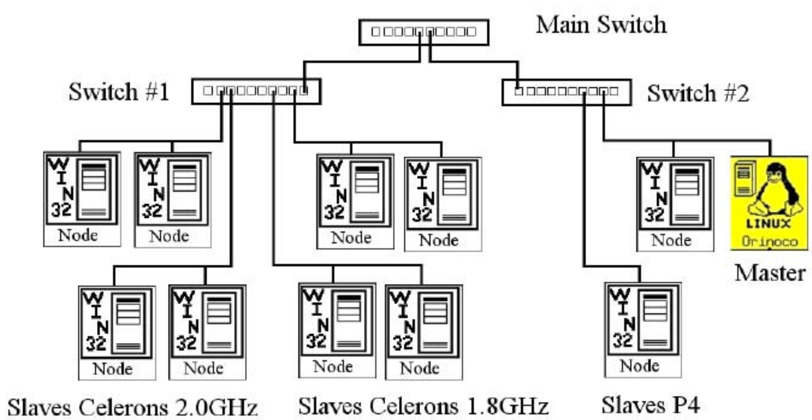

Figure 5. Cluster network topology

2.4.2 The Scheduler

In our case, the scheduler was build using a round robin procedure, taking in to account CPU clock speed, task in the pool to be processed and the number of processor. The nodes (PCs) of the cluster are dynamically ranked by speed, those nodes with multiprocessors a weight equal to the number of processor is given; if the numbers of task waiting in the pool are greater than the number of processor. This is done in order to reduce the communication load in the network.

3. Application to the Case Study

Belo Horizonte Drainage Network

3.1 Background

Belo Horizonte (BH)is the capital of the State of Minas Gerais, which in economic terms (gross product) is the third among the 26 Brazilian states. The city lies at 20° South latitude and 44° West longitude (Figure 6) and has an altitude of 750 to 1,300 meters. It is located in a mountainous region of tropical soils that originated from the decomposition of metamorphic rock. Tropical highlands weather predominates in this area, with average yearly rainfall of 1,500 mm and average yearly temperature of 26^{o}C. The rainy season lasts from October to March, when 90% of the total yearly rainfall occurs. The highest monthly average rainfall (315mm) takes place in December. Typical rainfall intensities are also relatively high (e.g.: 200 mm/h in the case of a 10-year return period event with 5 minutes duration; 70 mm/h for the 1h and 50-year return period event). Mean relative humidity reaches 50% during winter and 75% in summer.

Figure 6. Location of the municipality of Belo Horizonte

BH has 2,227,400 inhabitants with a population density of 6,900 inhabitants/km^2. It is a planned city, built in 1898 to become the capital of the state. The total area of the municipality is 330 km^2. BH is inserted into a metropolitan area; the RMBH (Belo Horizonte Metropolitan Area), gathering 33 distinct municipalities, with an area of 9, 179 km^2 and 3,900,000 inhabitants.

The Belo Horizonte territory locates at two main catchments (Arrudas creek and Onca creek catchments), each representing at about 50% of the total municipal area. Part of those catchments locates at neighbourhood municipalities: Contagem, upstream of Belo Horizonte, and Sabará and Santa Luzia, downstream of Belo Horizonte. There are no rivers in the municipal territory, although Arrudas and Onça are direct tributaries of the Velhas River, with a total drainage area of about 40,000 km2, which itself is the tributary of the Sao Francisco River, the longest one entirely within Brazilian territory (approximately 600,000 km^2 of drainage area).

Stormwater management has been entirely under the responsibility of the BH municipality since the city foundation. Traditional storm water systems prevail in the city, although experiences with detention ponds exist since the 50s. There are at about 4,300 km of roads all of them equipped with gutters, inlets etc. The municipal database on drainage infrastructure keeps details about 64,000 inlets (gullies), 11,500 manholes, 1,100 outflow structures (outfalls), and almost 770 km of stormwater sewers. There are some 700 km of perennial creeks in the municipal area. Part of those creeks have been lined, most of them as culvert concrete channels. The length of lined channels reaches near to 200 km (Figures 6).

The creek lining policy, which prevailed up to the 90s, was mainly justified by the following rationale:

- Lining is required for increasing the flow velocity and the channel conveyance, reducing the flood risk;
- Lining makes easy the implantation of interceptor pipelines and the so called sanitary roads;
- Lining makes easy the creek maintenance;
- Health risk due to directed contact with polluted waters may be reduced by creek lining;
- Inhabitants of riparian zones usually ask for creeks to be lined

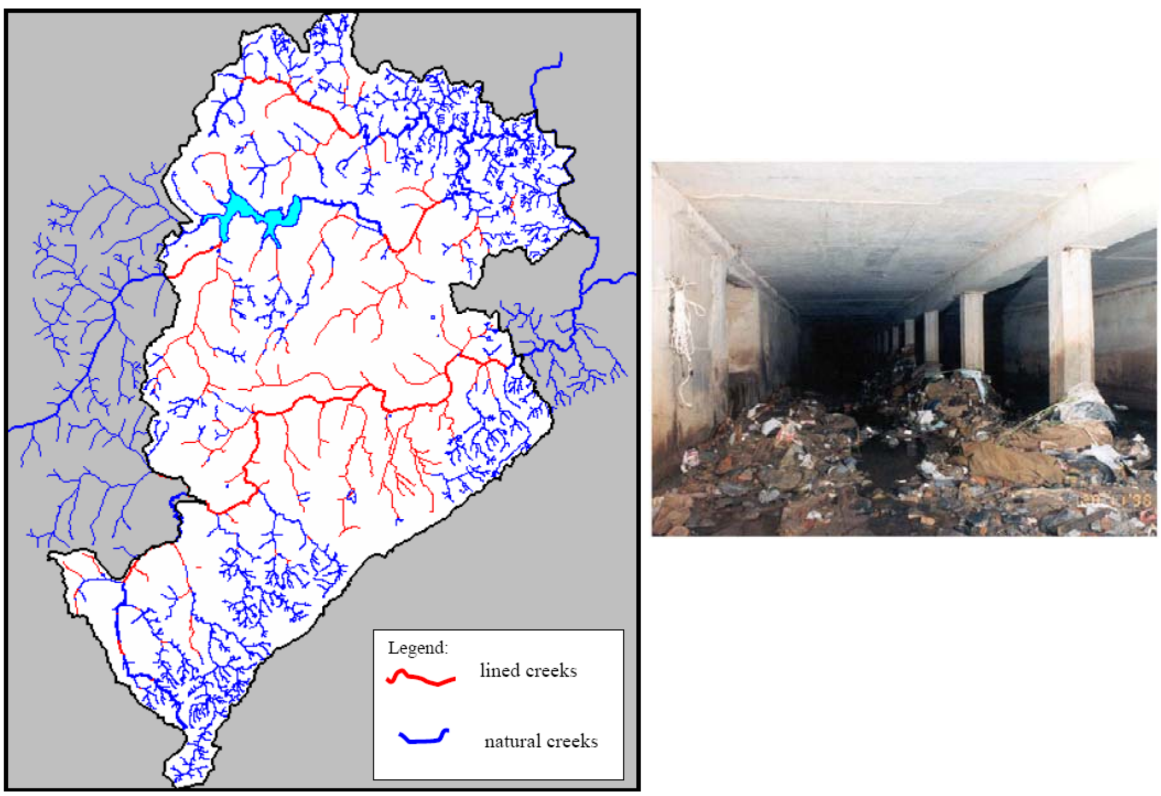

Figure 6. Belo Horizonte hydrography and lined channel photo

The apparent simplicity of stormwater management, as perceived almost during all the last century, led to the use of very simple design methods for storm water systems. Synthetic models were used which do not require observed data to calibrate parameters (e.g.: rational method and synthetic unit hydrograph). Since observed data were considered as not necessary for storm water management, during all the last century the BH municipality did not invest in monitoring stream discharges or water quality parameters. One of the consequences of those approaches is high uncertainty in hydrologic design. A similar oversimplification also prevailed in hydraulic design. Complex flow conditions, including the effects of stream confluence, flow transitions or unsteady flow, were infrequently regarded and model simulations of these conditions were rarely done. Only uniform flow conditions use to be In order to see the effects if the pipe network is increased, a new test was carried out using

3.2 Building and running the initial Model

A portion of Bello Horizonte drainage network was setup in Mouse to be tested. The topography and the information to build the model were provided by the local partners in the learning alliance. The information was Pre-processed in ArcGis 9.0 to define the sub-catchments and main streams. This part of the network corresponds to the Vendanova Catchment located in the North side of Belo. See Figure 7.

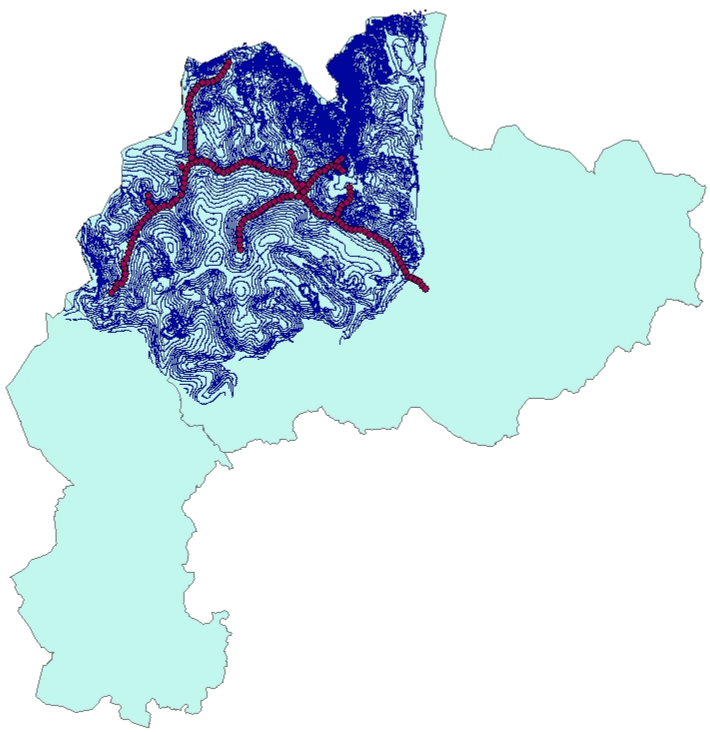

Figure 7. Layout of the Drainage network build for the case study (Vendanova Catchment).

The network is composed by 168 pipes and 169 nodes Figure 8. A rainfall event corresponding to a precipitation of 20 mm over a period of 6 hours was used for the simulation. Figure 8 shows the network schematization in Mouse.

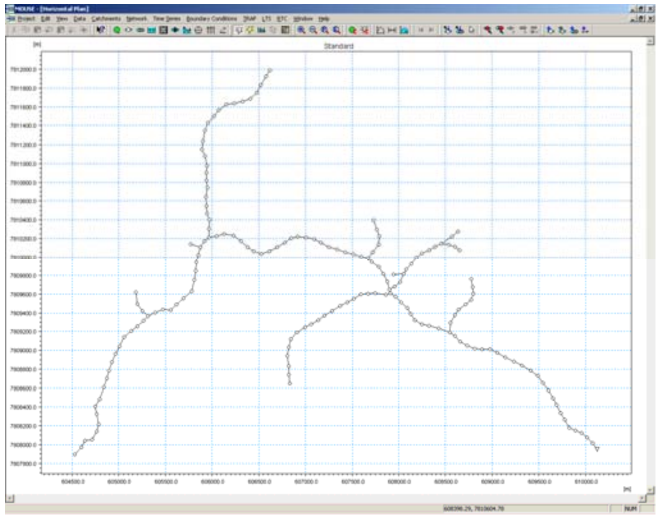

Figure 8. Network schematization in Mouse

The initial Run shows that there are some critical parts in the drainage network where most of the flooding occurs. Figure 9 shows the results of the initial run, the maximum flooding occurrence and a longitudinal profile of the main collector.

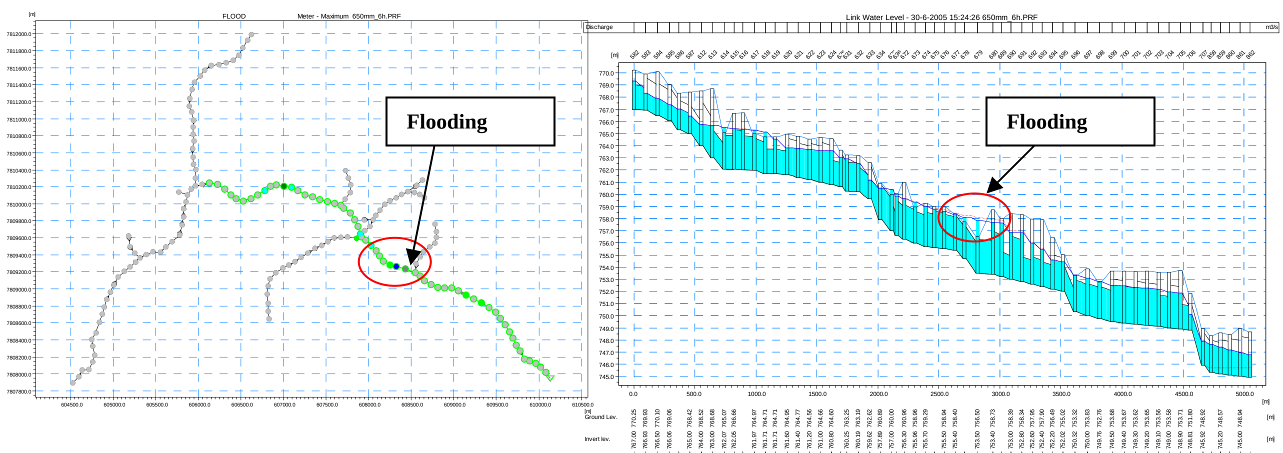

Figure 9. Initial Modeling Results (Plan View and Longitudinal Profile)

Figure 9 shows that for this rainfall event all the nodes that are flooded occur in the central collector of the system. The optimization process is setup to solve the flooding situation in the system with two objective functions, Flooding damage and pipe renewal cost. The total amount of pipes/channels that can be changed during the optimization process is 69. Each conduit (circular, rectangular or square) has on average 20 possible values in the catalogue. For this case the interface program was updated to manage circular, square and rectangular conduits. A new catalog conduit catalog is added for each type of section in the network. The total complexity of the optimization can be estimated as 69^{20} , which is 5.98^{36} possible combinations. This big number of possible combinations is not possible to handle by changes manually. This is one of the reasons to find sub-optimal designs in reality. And it is also one of the main arguments to use optimization techniques as the one evaluated in this case.

3.3 Optimization with NSGA II

To solve the flooding issues in the drainage network, the problem was formulated within an optimization process were flooding damage and pipe renewal cost are the functions to be evaluated.

The input parameters for the NSGA II were set to 48 individuals as population size and 200 generations. The total amount of function evaluation is 9600. The cross over parameter is set to 0.9 and mutation probability to 0.15. Figure 10 shows the evolution of the pareto front at the beginning of the optimization, at generation 10 and the last generation.

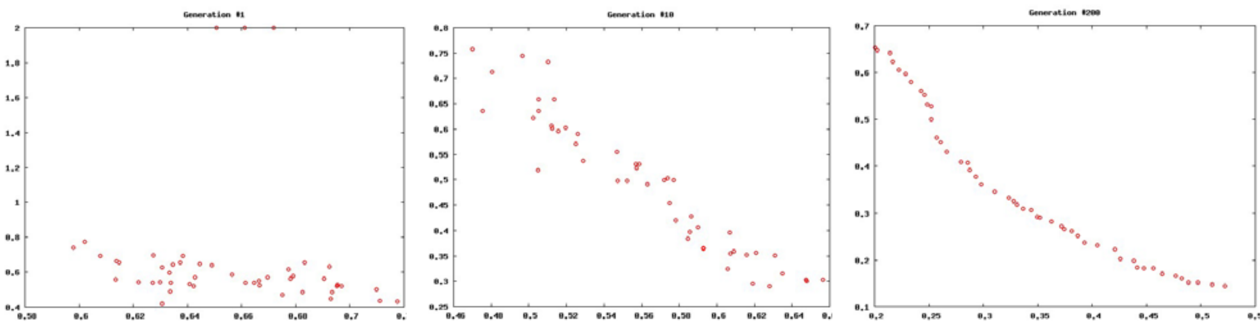

Figure 10. Pareto Front evolution with NSGA II

The experiments were carried out 5 times. A single run in a single processor took in average 81.54 hour. The calculation time depends on the speed of the processor of the CPU used. The final pareto set can thereafter be explored by the decision makers to decide upon the level of investment and benefits that can be achieved in the systems, since this is a trade off decision. The more money is invested in the system the lower is the expected damage caused by flooding.

3.4 Optimization with NSGAXp

The network was running using same approach that for the previous case, but this time the population size was set 48 individuals and the number of generation to 200. The total amount of function evaluation is 9600. Cross over is set to 0.9 and mutation probability to 0.15. The optimization was done using up to six processor. But this were using two INTEL Pentium IV, and two INTEL dual core. The idea this time was test other type of heterogeneity in the network topology, which is the use of the multiprocessor computers in the cluster conformation, the CPU speed for the Pentiums and the core duo processor was similar 2.4 GHz. The exercise was carried out 5 times and the same initial seed value was used.

Figure 11 shows the final result of a set of runs using different amount of processors. This figure shows that there is not a significant difference in the shape of the final pareto set found a t the en of the optimization loop. This is significantly important to guarantee that there are no major differences or changes as a result of the parallelization of the NSGA code.

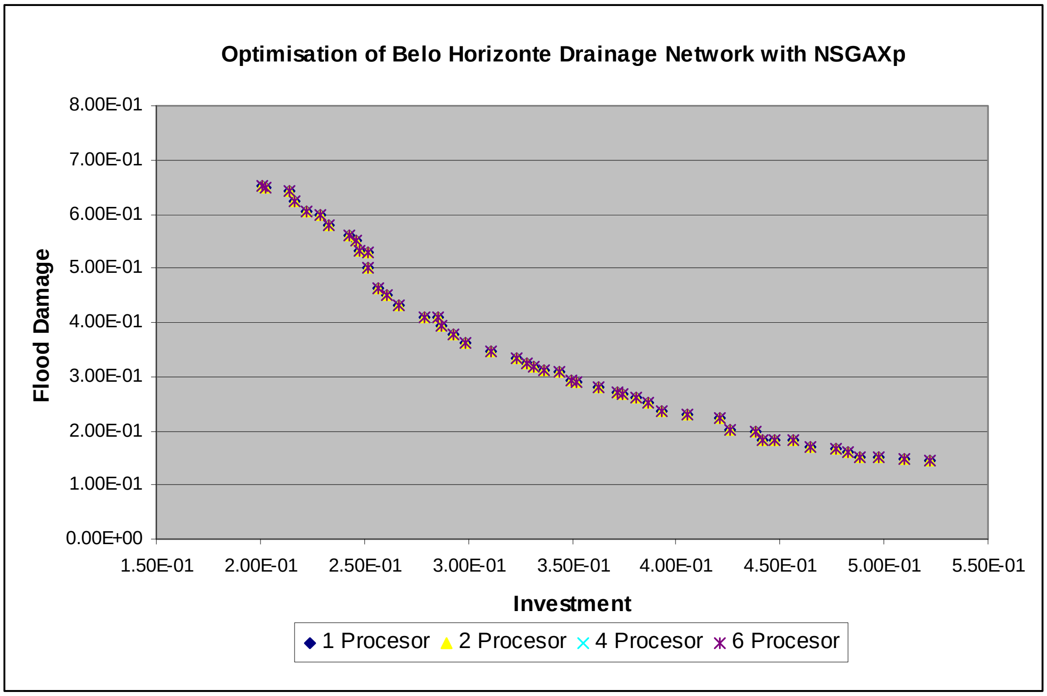

Figure 11. Pareto Front for different amount of processors with NSGAXp

As pointed out previously a single run in a single processor took in average 81.54 hour, while for the whole six processor it took 16.10 hours. A reduction 80.3% in time was achieved saving 65.5 hours for the whole optimization process.

To estimate the performance of the approach the speed up indicator was computed using Amdahl's and Gustafson's laws. Table shows the performance comparison using Amdahl's and Gustafson's laws. This time the estimate fraction of not parallelizable code was 0.04 and 0.16 respectively. Amdahl's law perform closer than Gusftason's but this time both are very close to real speed up.

Table 2. Real and theoretical speed up comparison

Number of Processor	Speed Up	Amdahl's law (f=0.04)	Gusftason's law (f=0.16)
1	1	1	1
2	1.94	1.92	1.84
4	3.62	3.57	3.52
6	5.06	5	5.2
8	---	6.25	6.88
10	---	7.35	8.56
12	---	8.33	10.24
14	---	9.21	11.92
16	---	10	13.6
18	---	10.71	15.28
20	---	11.36	16.96

Figure 12 presents the performance of the different runs against the theoretical speed up. The graph also presents the computed performance for another case. The other case corresponds to a less complex drainage network with only 12 pipes.

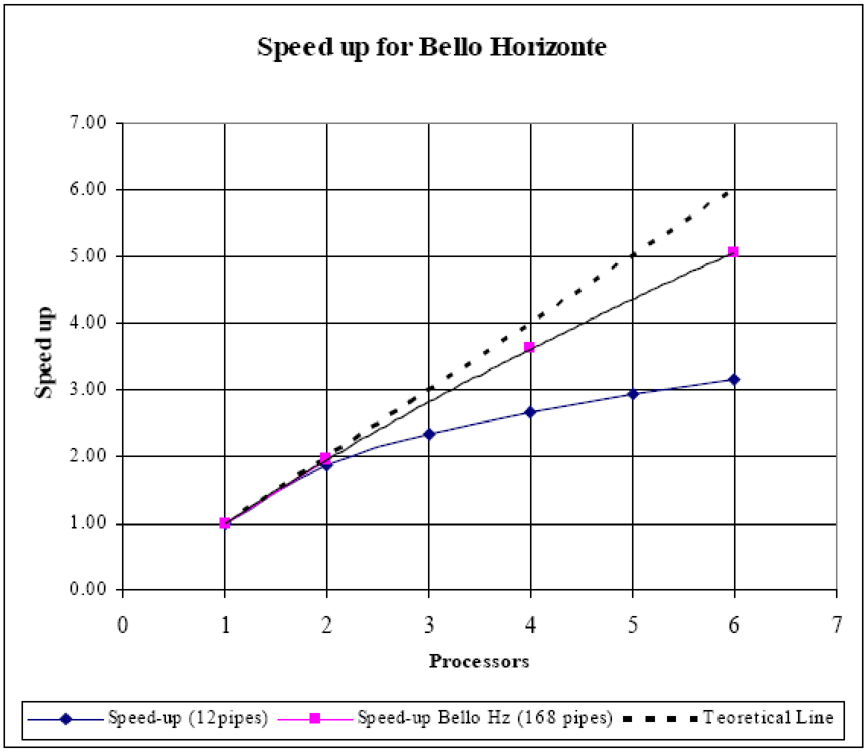

Figure 12. Speed Up performance for Belo Horizonte drainage network

Figure 12 shows that by increasing the size of the problem, the sewer network in this case, the performance of the cluster that runs the parallelized code is improved significantly. Parallel computing must be used to solve large problems. The approach can also be tested to increase the size of the population and generation used within the optimization process and refined further the pareto front.

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