Using the Fast Multi-Objective Genetic Algorithm to Improve the Urban Flood Modeling

M. Rezoug, R. E. Meouche, R. Hamzaoui, and Z.-Q. Feng

Abstract—**In the present paper, a multi objective optimization approach based in Genetic Algorithm, Design Of Experiments and Response Surface Method strategies, is applied in order to predict the optimal CFD model parameters, allowing to model with high accuracy the 3D free surface flow of urban flood propagation retaining the total computation time (CPU-time) as short as possible. An experimental data set was used in this study as a validation means for numerical optimized models. We can say that the constraints in terms of computation time and accuracy, related to the application of 3D CFD modeling for flood propagation problems can be overcome by making an optimal choice of the advanced parameters of model.**

Index Terms—**Urban flood modeling, computational fluid dynamics (CFD), multi objective optimization problems (MOOP), genetic algorithm (GA), response surface method (RSM), design of experiments (DOE).**

I. Introduction

Flooding in urban areas is an inevitable problem for many cities in the world [1]. A numerical simulation able to provide realistic representation of the urban flood propagation in which we can see flood water propagation versus time over the streets, is essential to estimate of losses from future floods and also to prepare for a disaster and facilitating good decision making. However, there is still a lack of being able to represent the dynamic propagation of the flood in the real 3D urban area model with quite good accuracy, on the one hand because of the complexity of the flow in urban areas (Presence of the multiple obstacles) requiring generally a huge computing time and on the other hand because of the lack of knowledge regarding good modeling parameters used to better predict of flow behavior. One of the most powerful approaches is based on three-dimensional Computational Fluid Dynamics (CFD) modeling combined with 3D topography data [2], [3]. However the great limits using such method is the high computations time, often estimated in hours to days depending on the complexity and size of the problem. ANSYS®CFX® [4], a state of the art CFD package, is used to perform 3D free surface water flow modeling. The package uses a finite volume method associated with a k-ε turbulence closure model [5] to solve the Reynolds-averaged Navier-Stokes (RANS) equations [6]. The water-air interface is captured with the volume of fluid (VOF) method [7]. The objective of the present paper is to explore through a multiobjective optimization method, a process of improving the performance of the CFD model to adapt it to model with accuracy and efficiency the flood propagation problems, in urban areas.

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M. Rezoug, R. E. Meouche and R. Hamzaoui are with the Institute of Research on Constructibility –ESTP Paris, 28, avenue du Président Wilson - 94234 Cachan cedex, France (e-mail: rezoug@profs.estp.fr).

Z-Q. Feng is with the EVRY Laboratory of Mechanics and Power. Evry University, 40 rue du Pelvoux, 91020 Evry, France.

II. Methodology

Among the main parameters of the CFD model, six were chosen to be the subject of this study. We start by assess their impact on the results and then predict the optimal values of them leading to minimize the error between the experimental and numerical results as well as the total CPU-time. The first set of these parameters is he constants of K-epsilon model; $\mathbf{C_{\varepsilon 1}}$, $\mathbf{C_{\varepsilon 2}}$, $\mathbf{C_{\mu}}$, and the second one is the meshing parameters; First prism height, Expansion factor and Number of Inflated Layers. Through an iterative process, a multiobjective optimization algorithm is used to find the different optimal combinations between these parameters, leading to satisfy the problem objectives which are (i) Maximize the accuracy of the results. (ii) Minimize the computing time (CPU time).

III. Experimental Data and CFD Modeling

In order to assess the effect of optimal parameters predicted on results and objectives covered, we need to rely on experimental results as a basis for comparison. Some data of IMPACT European project have been used as test cases for verifying the performance of our optimized numerical results [8]. The water level as well as its velocity in the x-direction is measured by means of water level gauges and ADVs probe in 5 points located around the building as shown in Fig. 1(a).

The initial conditions consist in a water level of 0.40 m in the upstream reservoir and a thin layer of 0.01 m of water in the downstream part of the channel. The test duration is 30 s. After the rapid opening of the gate, the strong dam break wave reflects against the building, almost submerging it, and the flow separates, forming a series of shock waves crossing each other.

An initial CFD simulation is performed and the comparison of its results with the experimental one is taken as reference for the optimization strategy as is detailed in the next section. The computational domain was meshed using 40,000 cells. Iso-surface of water height colored by the velocity magnitude at t = 10s of experience time is shown in Fig. 1(b). The computing time on a dual processor Intel Core i5 machine, 3.07 GHz and 16 GB of RAM, of this CFD simulation takes approximately 4 hours. The comparison between the experimental and numerical evolution of the water level and the velocity in the x-direction at each gauging point is presented by Fig. 3 (a) and Fig. 3 (b), respectively.

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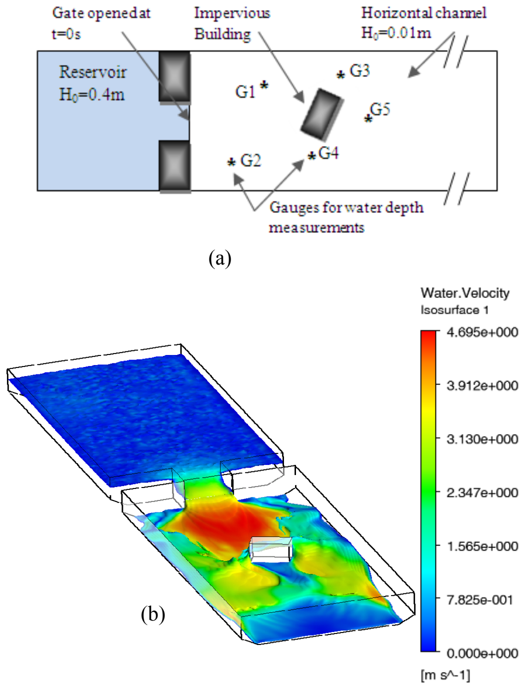


Fig. 1. Case study. (a) Experimental set-up. (b) CFD modeling Iso-surface of water height colored by the velocity magnitude at t=8s of the simulation.

IV. Optimization Cycle

Every Modeling steps are automatically managed by the multi-objective optimization package of modeFRONTIER® [9], after a series of initializing. The six CFD parameters are defined in the optimization processes as input variables, and named $x_1$to x_6. The input variables are inserted in the CFD journal file, where the model parameters are defined, so that changing the values of these input variables change accordingly the model parameters. ModeFRONTIER® runs ANSYS®CFX® in batch by feeding it with the current CFD journal file having all the commands for the simulation and post processing in order to modify in the first time the mesh parameters (x_1, x_2 and x_3). The mesh file is passed then to the CFX preprocessing step where the constants values of the K-ε model (x_4, x_5 and x_6) are modified before passing to the CFD solver. The evolution of levels and velocities of water versus time in five points of the channel are calculated and defined as CFD results. These latter are written into an ASCII output file. A Matlab® script was developed in order to facilitate and speed up the processing of results. It consists in calculating in each point (G_1 to G_5), the error between numerical and experimental curves for both water velocity (Error_WV) and the water level (Error_WL) using the average of relative errors method.

V. Results and Discussion

As a first step for the selected optimization strategy, a preliminary exploration of the design space is performed using Uniform Latin Hypercube [10] DOE (Design Of Experiments). Using this method, 20 points are created and distributed in the design space according to a uniform distribution applied to each of the input variables defining the optimization problem. A Fast Multi-Objective Genetic Algorithm (FMOGAII) based on the integration of robust multi-objective genetic algorithm (MOGAII) and the efficiency of the Response Surface Methodology (RSM) is used starting from the set of the design data (DOE) as an initial population to obtain the Pareto frontier (set of not dominated designs) concerning the three objectives that we want to minimize. The Response Surface is used to automatically extrapolate the response of the system in function of the design variables. In this way, a full virtual optimization step can be performed (virtual in the sense that CFD application is not evocated, but results are extrapolated directly from the RSM mathematical Meta-Models), including a local refinement DOE phase around the best solutions, while the best solutions so far obtained (Pareto frontier) can be validated using real simulations, updating this way the Response Surface Meta-Models with the new real designs evaluated in following steps, until a convergence is reached (Fig. 2(a)).

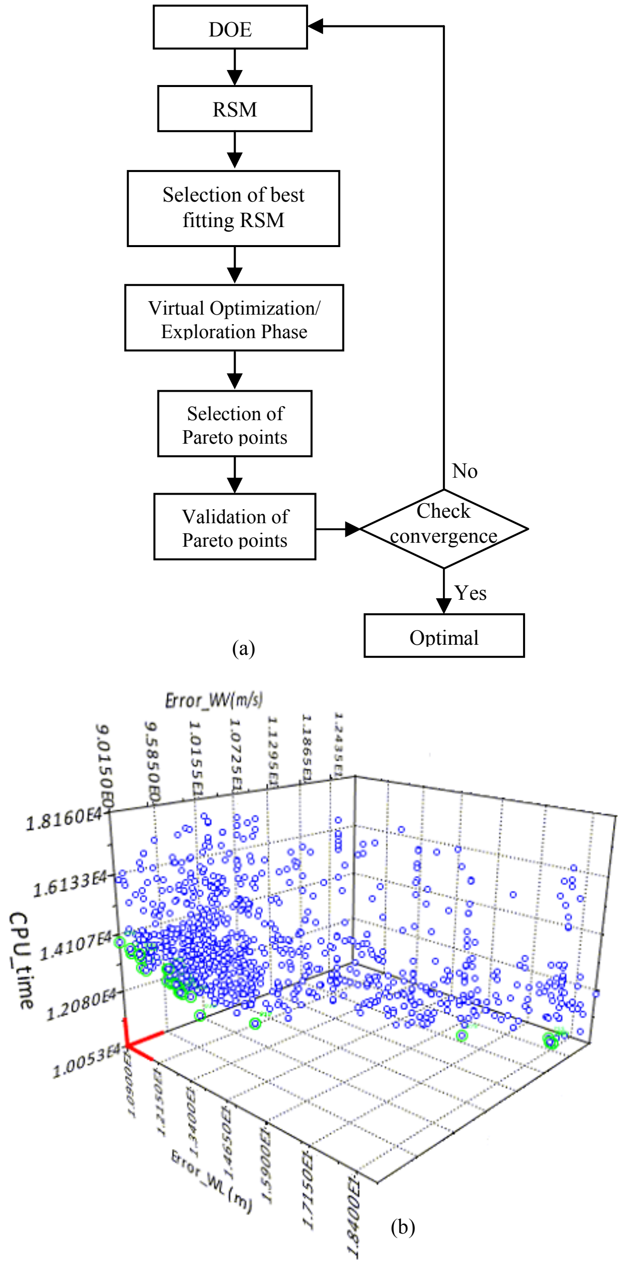


Fig. 2. Optimization charts. (a) FMOGAII algorithm. (b)The objective space with non-dominated solutions and the Pareto front of the problem (marked in green).

The objective space that is constructed by minimization of the three objectives is shown in Fig. 2(b). Pareto frontier, have been selected from the entire objectives space. The chart clearly illustrates that the best designs, corresponding in the Pareto front, all have low values. This confirms the nature of the multi-objective Genetic Algorithm and how the designs improve after each generation.

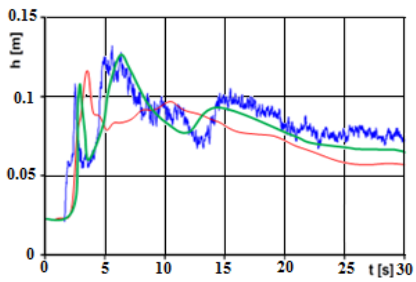
Three interesting solutions have been selected from Pareto front and compared with experimental and reference CFD results. Δ is the percentage of Errors reduction compared to the reference CFD results. All the objectives have been significantly improved (minimized), and the results are summarized in the Table I.

TABLE I: SOME PARETO SOLUTIONS FOR WHICH THE OBJECTIVE FUNCTIONS ARE MOST MINIMIZED.

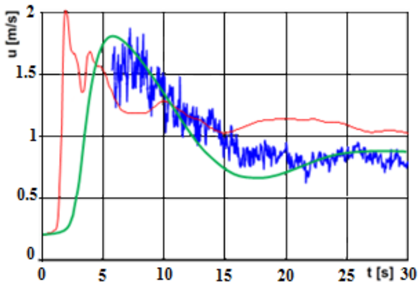
Pareto solutions	Δ [%]	Δ [%]	Δ [%]
ID 896	3.94	67.42	59.42
ID 406	30.67	25.51	20.04
Trade-off	27.7	50.58	48.22

With ID 896 is the design having the lowest Error_WL and Error_WV, ID 406 is the design having lowest CPU_time. The trade-off solution is the design that is a good compromise for the three conflicting objectives.

Modeling results corresponding to the trade-off solution (optimal CFD parameters) are presented and discussed. Fig. 3(a) and (b) show the evolution of the water level and water velocity, respectively at gauging point named G4, comparing experimental results with the reference simulation and the optimized ones.



(a)



(b)

Fig. 3. Comparison of the water evolution at gauging point (G_4). (a) The water level. (b) The water *x*- velocity

From these pictures we can clearly see the effect of optimization in terms of improving the simulation results, where we can observe that the optimized simulation has predicted quite well the evolution of water levels as well as the fluctuating behavior of the water flow for all points. While that of the reference simulation could not simulate small decreases and increases of the water level; this solution smoother than the actual one is due to the poor choice of CFD simulation parameters. The gap between experimental and optimized numerical curves is significantly reduced on all points. Like the evolution of water depth, the velocity is generally better estimated by the optimized solution. Concerning the delay that appears for the gauging points situated upstream the obstacle between the experimental and the numerical results, we can interpret it by an abnormal initialization time for measurement tools, because it is regular and constant (approximately 0.5 seconds) for all curves. This confirms that the Multi Objective Optimization strategy has allowed predicting the better CFD parameters to reproduce the behavior of the flow with accuracy close to real. From Table 1 and Fig. 3 it can be noted that CFD parameters which are used to obtain the Trade-off Pareto solution, are among the optimal CFD parameters that can provide accurate results in less time for a similar problem, i.e. flood propagation due to dam/dyke break waves.

VI. CONCLUSION

This paper has presented a procedure based on multi-objective optimization strategies, aims to help the user to speed up the choice of correct parameters ensuring simultaneously the accuracy and efficiency of the CFD model. A general strategy based on FMOGA has been presented to found optimal CFD parameters minimizing errors of water level and velocity, as well as the total CPU time. The study in this paper was limited to evaluate the effect of only six modeling parameters on the accuracy of results, in order to increase the efficiency of the optimization to improve better results, it is recommended to increase the number of parameters in the optimization processes. This work has demonstrated the effectiveness of Multi-Objective Optimization techniques in improving the flood propagation modeling in urban area. 3D CFD modeling seems perfectly suitable for analyzing the details of the dam break flows near the dam; for example to investigate different failure scenarios, for calculating the discharge hydrograph caused by the dam failure and especially for studying the interaction between the flood wave and nearby structures (e.g. buildings, bridge).

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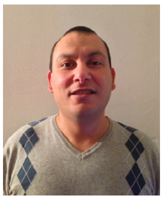
Mehdi Rezoug is an assistant professor in the Constructibility Research Institute (ESTP/IRC–France); his principal research interests lie in the field of Multicriteria Optimization and Multiphysics Modeling in mechanics and civil engineering.

For his PhD, he developed a numerical method to construct a three-dimensional model of complex urban areas using specific programming methods combined with GIS data and CAD software in order to study different flooding scenarios. A great part of his thesis was also interested to explore the different solutions and spatial planning projects to be made in urban environments in order to reduce the risk caused by the floods. In this context, a multi-criteria optimization approach based on evolutionary algorithms has been developed and coupled with the preparametered CFD modeling in order to find the optimal configuration of the city representing the least risk and the maximum comfort.

Rani El Meouche is an associate professor in the Constructibility Research Institute (ESTP/IRC–France), and He received Master's Degree in Engineering/Surveying from ESGT – LE MANS, France, M.S.c in Geographical Information Sciences from University of Marne La Vallée, France, and Ph.D. degree from the same university in 2007.

His principal research interests lie in the field of Geomatics/Surveying Engineering, 3D Modeling, BIM, GIS and GNSS.

Currently he is the head of the department of surveying and Geomatics in ESTP.



Rabah Hamzaoui is researcher scientist from IRC/ESTP Cachan France. He has professor grade (HDR). I have worked in nanomaterials obtained by mechanical alloying and their properties (magnetic, mechanic, structure….) since 1998. Actually, He is interested by construction materials (concrete, mortar, soils,…). His main objective is to introduce Nanomaterials in construction materials in order to propose smart construction materials.