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Multi-Agent Approach to Biofilm Development in Water Supply Systems

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Multi-Agent Approach to Biofilm Development in Water Supply Systems

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Abstract

The presence of regulated quantities of residual disinfectant is a usual feature in water supply systems (WSSs); nevertheless, biofilm formation persists in all of them, representing a paradigm in WSSs management due to the numerous undesirable problems associated. This study attempts to create a biofilm model based on a limited number of basic interactions between bacteria and the hydraulic and physical characteristics of the pipes by the step-wise evolution of biofilm over time. Multi-Agent Systems (MASs) are used as a modelling tool to achieve this purpose, arising as an excellent starting point for further researches. A MAS consists of a population of autonomous entities (agents, biofilm bacteria in this case) situated in a shared structured framework (environment, pipes in this case). These agents operate independently but also are able to interact with their environment, coordinating themselves with other agents. By obtaining a MAS based biofilm model, it will be possible to achieve a better understanding on any situation of interest because different research scenarios could be simulated allowing to check the hypotheses on their mechanisms and to predict how biofilm evolves in WSSs.

Keywords: Biofilm, multi-agent systems, water supply systems

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Introduction

In the last years, different aspects have led to focus the interest in improving the protection and control of the drinking water quality in its distribution, after treatment. It is known that the design of the distribution systems inevitably causes the decay of the water quality. However, most of the times, the system design, by itself, does not explain the extent of this decay. The reasons for a high deterioration of the water quality in the distribution systems are not entirely clear, but it is known that one of the main actors involved in this decline is the biofilm development in the inner pipe wall. The distribution systems are the major components of the water utilities and numerous processes and physical, chemical and biological reactions take place inside them. It can be said that water supply system (WSSs) pipes resemble biofilm growth reactors, with a set of complex components and reactions which vary in time.

Biofilm is a complex structure of the microorganism communities that develop in the presence of water, adhered to surfaces and coated by a protective layer segregated by themselves. Thus, the biofilm's bacteria are capable of withstanding biocides and antibiotics more effectively than the free-living bacteria, supporting significantly higher doses of antimicrobial. Apart from the health risk that these communities of microorganisms represent in WSSs due to their role as pathogens reservoir, their presence in these systems is also associated with many other negative aspects that favour the decay of water quality in the distribution systems. In fact, biofilm is responsible for many of the problems encountered in these systems. The most prominent are: aesthetic deterioration of water [1], proliferation of higher organisms [2], operational problems [3], increased corrosion rates [4] and consumption of disinfectant [5].

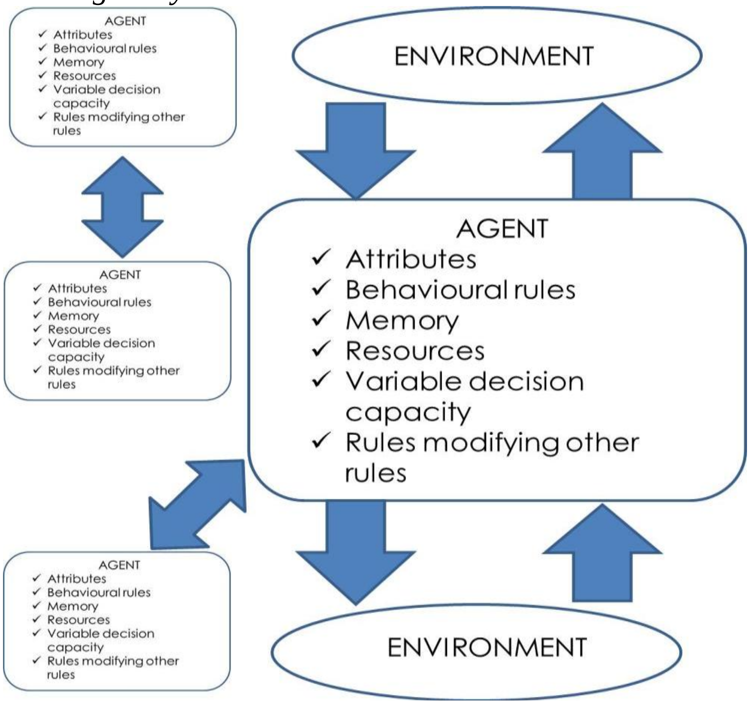
This article aims to represent, through the use of Multi-Agent Systems (MASs), the formation of biofilm within the WSSs pipes, based on a limited number of interactions among bacteria, hydraulics and the physical characteristics of the pipes. Thus, developing a decision-making support tool that enables the observation of the processes occurring inside the pipes and alleviates to some extent the lack of knowledge associated with the inaccessibility in these systems is the main objective of this paper.

The present work is divided into the following sections. In the next section we explain the multi-agent systems. In section "Modelling the Biofilm Development Process" we present the obtained results after the development of the model. Finally, we close the paper with some conclusions and recommendations.

Multi-Agent Systems as Modelling Tool

MASs are used as a modelling tool to fulfil the goal of this paper. In the field of water, it is not the first time that these systems are used; in fact, the trend in recent years has been to include multi-agent techniques as an interesting alternative to solve complex problems. In urban hydraulics, specifically, we find several recent examples such as [6] and [7].

Figure 1. *Multi-Agent Systems*



A multi-agent system consists of a population of autonomous entities (agents) situated in a shared structured framework (environment) [8]. These agents operate independently but are also able to interact with their environment, coordinating themselves with other agents (Figure 1) [9]. This coordination may imply cooperation if the agent society works synergically. Thus, in a cooperative community, agents have usually individual capabilities which, combined, will lead them to solving the entire problem. But cooperation is not always possible and there are instances where agents are competitive, having divergent goals. In this later case, the agents also should take into account the actions of others. However, even if the agents are able to act and achieve their goals by themselves, it may be beneficial to partially cooperate for better performance, thereby forming coalitions. Turning on to coordinating activities, either in a cooperative or a competitive environment, one basic way to solve the potential conflicts that may arise among agents is by means of negotiation, interactions based on communication and reasoning regarding the state and intentions of other agents [9]. There are some properties which agents should satisfy [10]: reactivity, perceiving their environment; pro-activeness, being able to take initiative; and social ability, interacting with other agents. Besides, the agents are computationally efficient because concurrency of computation is exploited as long as communication is kept minimal. We deploy agents with redundant characteristics, which offer system reliability [11]. Since the agent modularity allows handling their properties locally, this system is easy to maintain. Agents solve different problems adapting their activity on different environments by organizing themselves. Regarding the environment, their more important characteristics are the next: it structures the multi-agent system as a whole; and it manages resources and services, maintaining ongoing activities in the system and defining concrete means for the agents to communicate [9].

Biofilm modelling allows checking hypothesis on their mechanisms. The agents are defined as bacterial colony cores; due to the high biofilm density reached in these systems. Theses cores mimic the behaviour of individual bacteria. Once agents have been defined and their relationships established, a schedule of combined actions on these objects define the processes occurring, in their environment, over time. In this study the environment is represented by the inner part of a pipe where biofilm develops.

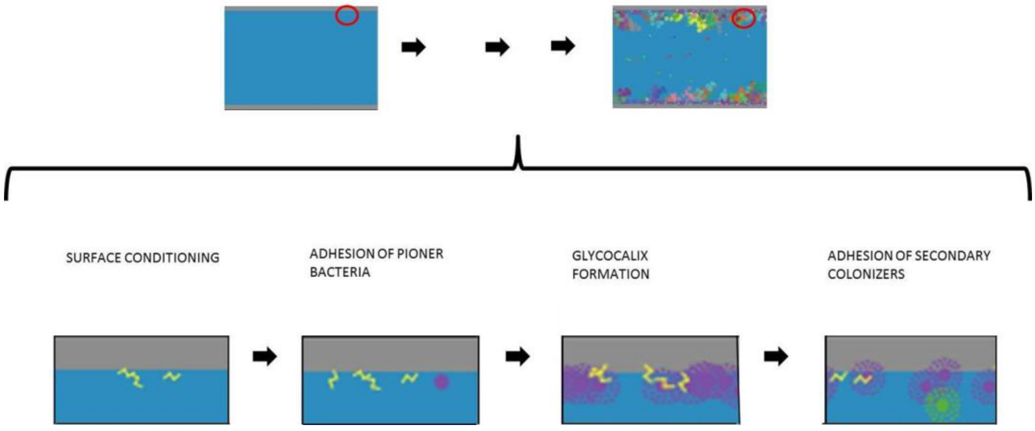
Modelling the Biofilm Development Process

The model has been developed in the NetLogo software [12]. One of the purposes of this study was to build a model as generic as possible, with no assumptions about the nature of the biofilm or the type of the microorganisms that compose it, that can develop the biofilm formation stages in WSSs. Due to computational constraints, and the selected simulation scale, the high concentration of microorganisms occurring in biofilm does not allow us to model each individual bacterium. The agents were defined as clusters of colonies of bacteria due to the high bacterial densities reached in these systems. Each agent represents a core, a bacteria colony, and is capable of binding to the pipe wall, excrete glycocalix, reproduce (create new agents), die and detach from the biofilm. This last action will depend on the flow velocity and the position of the agent in the matrix model. The environment model has been described as the inside of a pipe.

In the instant that a clean pipe is filled with water, the biofilm begins to form. Any surface immersed in water instantly attracts, both, organic and inorganic molecules from the water that surrounds it, forming a preparation film. The formation of this initial film is especially important in environments that are low in nutrients, such as drinking water, where the accumulation of organic molecules on the surface creates a localized area relatively rich in nutrients. Some of the planktonic bacteria will approach the pipe wall and become entrained within it [13].This initial attachment is based on the electrostatic attraction and physical forces, not any chemical attachments. Some of the adsorbed cells begin to make preparations for a lengthy stay by forming structures that may permanently attach the cell to the surface [14]. Biofilm bacteria excrete extracellular polymeric substances, or sticky polymers (glycocalix), which hold the biofilm together and cement it to the pipe wall. As nutrients accumulate, the pioneer cells proceed to reproduce [13]. The glycocalyx net, apart from trapping nutrient molecules, snares other types of microbial cells through physical restraint and electrostatic interaction (second colonizers) [14].

In summary, the steps to develop a mature biofilm are: surface conditioning, adhesion of pioneer bacteria, glycocalix formation and incorporation of secondary colonizers. All these steps have been incorporated in our model (Figure 2).

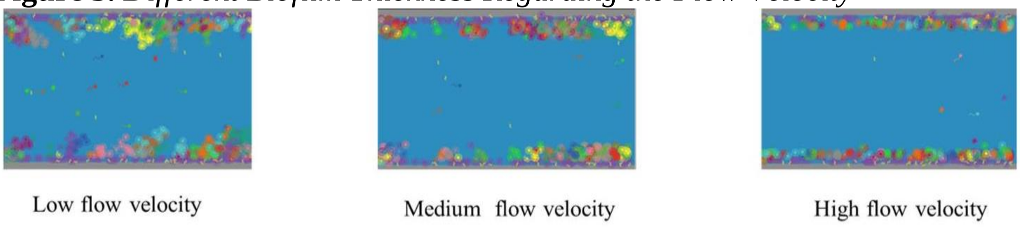
Figure 2. *Steps in Biofilm Development*



True biofilm steady state is never achieved, since selection is continually occurring, and slight changes in environment conditions may favour the growth of different organisms [15].

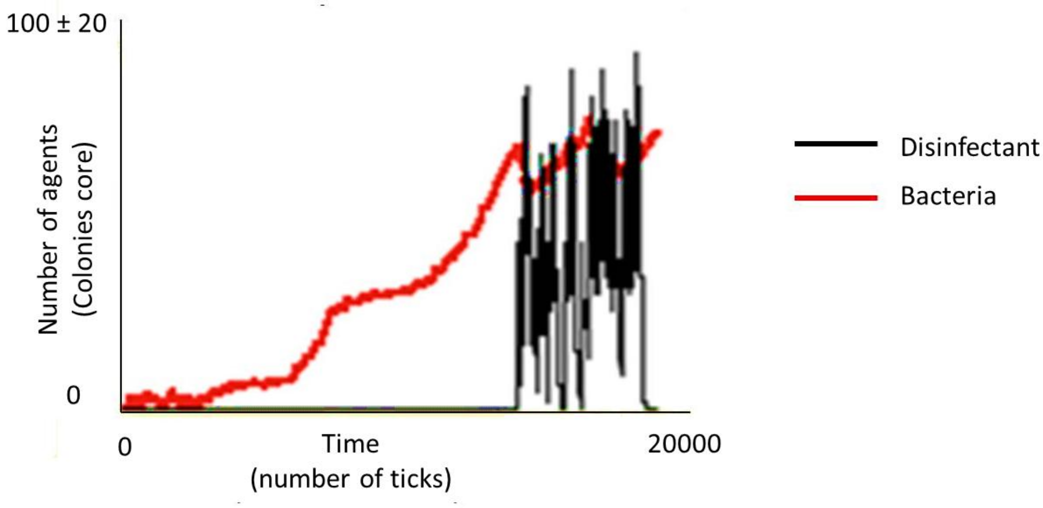
Shear forces or residual disinfectant are some of these factors that cause this biofilm instability. Shear forces exerted by flowing water impact on the mechanical stability of biofilms causing the continuous erosion of the surface layers and population succession. Indeed hydraulic shear can limit biofilm thickness [16]. Increasing the shear force decreases the thickness of the boundary layer (Figure 3). Agents interact with each other to find the balance between density and spatial growth.

Figure 3. *Different Biofilm Thickness Regarding the Flow Velocity*



Despite the presence of disinfectant residual biofilm exiting in all the WSSs, disinfectants represent a stress to these bacteria communities reducing their development in these systems. Even this is just an approach and deeper researches must be carried out, the effect that the different concentrations of residual disinfectant have in biofilm development or the biofilm recovery after the exposure to chlorine boosting, among others, could be studied thanks to this kind of models (Figure 4).

Figure 4. *Bacteria/Disinfectant Ratio*



Conclusions

This study provides an innovative work in the study of biofilm in WSSs with the introduction of multi-agent models as a new tool. It allows us to use the level of knowledge reached on the development of biofilm in a practical and efficient way. Introducing the MASs in shaping these communities provides an adaptive framework to get deeper knowledge of biofilm's ecology in WSSs, to check hypotheses on their mechanisms and to predict its evolution depending on time.

Agent-based modelling has demonstrated to be a powerful approach to achieve the better understanding of the processes occurring within the pipes. It helps to develop a new decision-making support system, enhancing the water quality management in WSSs. If more research is carried out in this direction, improvement of the mitigation of the problems associated with biofilm development in WSSs, and increase of management effectiveness of drinking water utilities, will be managed.

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