Hydro- and morphodynamic simulation considering ecological model components on asynchronous parallel Cellular Automata

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Abstract: In future, ecological aspects will play a major role for planning processes in coastal engineering. Coastal protection measures interfere with the environment, mostly restricting natural processes with sometimes undesired effects on coastal ecosystems. It is necessary to have appropriate tools to estimate these influences.

In this paper, a numerical simulation model which describes hydro- and ecological processes is presented. This consists of a discrete ecological model based on a Cellular Automaton and a hydrodynamic finite element model component. Possible transfer strategies, which allow a direct coupling between these different model paradigms, are presented. Main effects and possible influences on a changed hydro- and morphodynamic are shown with first academic tests. At last, an asynchronous parallel implementation for the efficient parallel computation of the Cellular Automaton ist introduced.

Keywords: FEM-CA coupling, parallel asynchronous simulation, Cellular Automata, ecological modeling, fuzzy logic

1 Introduction

The aim of coastal engineering is to estimate the effects of coastal protection structures. During the planning phase it is necessary to have appropriate hydrological and numerical models. Numerical simulations in coastal engineering allow estimations and forecasts regarding to the change of the environment by human interferences.

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Until now, a variety of hydro- and morphodynamic models has been developed to describe the physical processes. These models typically consist of a system of partial differential equations (PDEs), which are usually solved approximately using FEM, FDM or FVM.

Although a variety of appropriate models for the description of abiotic variables are developed and proved in the past, the characterization and simulation of populations and especially the interaction between hydrodynamic variables and ecological considerations is not well researched. In the future, ecological aspects will play a major role in planning processes of coastal engineering. Hydraulic engineering projects concerning coastal zones meet sensitive ecosystems characterized by a network of relationships between biotic factors and effects of physical processes. Often, the consequences of human interferences are negative effects on the biodiversity of these systems. That is why coastal protection structures have to comply with new ecological general conditions. Moreover, populations and the natural cover affects the hydro- and morphodynamic. Today's hydrodynamic models do not sufficiently consider influences by biotic factors and therefore cannot consider the interaction between hydrodynamic and biotic values. Therefore, the extension of current hydrodynamic models by an ecological model component is necessary, which allows the estimation of the propagation of seagrass and the interdependence with hydrodynamic parameters. Especially the sensitivity of the water subsurface to erosion is primarily influenced by the existence of animals and seaweeds. Ecological models are usually described by rules and relationship-diagrams which show the positive and negative dependencies between different populations and physical variables. For the analysis and description of local and time variant processes in ecology, especially Cellular Automatons have been proved as a suitable simulation tool.

2 Cellular Automatons

Cellular Automatons (CAs) are successfully used in different fields of ecosystem research and are able to describe local and time variant dynamics of populations organization (e.g. [2]). CA's are abstract models of computation and discrete dynamic systems. A CA consists of many cells created by dividing the region which the objective organisms inhabit. Each cell can obtain a state from a finite set, and the automaton evolves in discrete time steps, changing the states of all its cells according to a local rule, homogeneously applied at every step. The new state of a cell depends only on the previous state and the states of the cells adjacent to that cell.

A Cellular Automaton can be defined as a structure $CA = (\mathcal{L}, \mathcal{Z}, \mathcal{N}, \delta)$, where

- $\mathcal{L}$ is a regular lattice
- $\mathcal{Z}$ is a finite set of states
- $\mathcal{N} \subseteq \mathcal{L}^n$ the neighborhood
- and $\delta : \mathcal{Z}^n \to \mathcal{Z}$ is the local transition function or a set of local rules.

3 Ecosystem seaweed

To exemplify the modeling of ecological systems, we consider seaweeds and their dependencies in the mudflat of the North Sea (see figure 1) in this paper. This is the fundament for the presentation of a discrete ecological model, based on a cellular automaton, in the next section. Seaweeds are habitats for different kinds of species. Also, stabilising effects to the sediment are observed in areas of seaweeds. Especially the sensivity of the watersubsurface to erosion is primarily influenced by the existence of animals and seaweeds. Furthermore, the dense carpet of leaves is able to raise the flow resistance. Thus, ocean surface currents and wave motion can be reduced ([4]).

Figure 1: Sea grasses in the mudflat of the North Sea

Special experiments (see [6]) showed that the complex interaction between flow velocities, the densities of algae and snail populations plays a major role for the growth of seaweeds. In areas with low flow velocities the snails graze on the algae which live on the leaves of the seaweeds. But in areas with higher flow velocities the snails are flushed away. In consequence, the algae populations could not be grazed by the snails. High concentrations of nutrients in the sea can lead to an overgrow with algae on the leaves of the seaweeds in these areas. This has negative effects on the growth of the seaweeds because of the reduced photosynthesis. Other dependencies are the water temperature, the water depth and the cloudiness of the water. These model parameters and their dependencies among each other can be shown in a relationship-diagram (see figure 2).

4 A Cellular Automata based model of seaweeds

A Cellular Automaton can express the prosperity and decay of organisms affected by the variation of environmental factors. We consider a two-dimensional domain Ω, which is divided into a rectangular lattice $\mathcal{L}$. This lattice consists of $m \times n$ unique

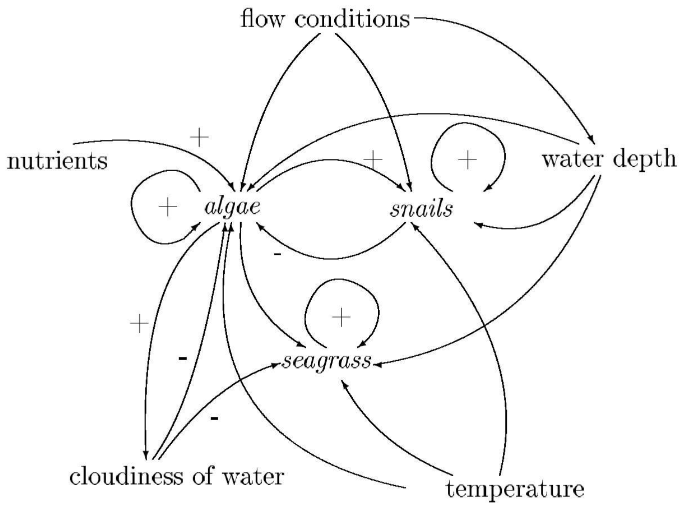

Figure 2: Dependencies between the considered model parameters

cells. Each cell $c \in \mathcal{L}$ of the Cellular Automata represents a small section of the sea. The following state variables are introduced:

- G: the density of the leaves,
- S: the density of snails,
- A: the density of algae,
- H: concentration of nutrients
- Z: the water depth
- V: the current flow conditions (v_x, v_y, η)
- T: the water temperature
- B: the cloudiness of the water

Note that we have enlarged the paradigm of classical CAs in order to use continuous state variables. Furthermore, we have to consider that many physical and biological systems are inhomogeneous. The local hydrodynamic and the population densities vary significantly in time and space.

Defining the rulebase using fuzzy-theory

A rulebase was defined, which describes the relationships and dependencies among these state variables. In ecology, the knowledge about the evolution of the populations is obtained by monitoring and experiences, which of course contains uncertainties. It is necessary to handle uncertainties in the variables and rules. Furthermore, a corresponding reasoning component is needed. The aim of uncertain reasoning is to deduce conclusions from fuzzy premises with a formal mathematical model. By using classical set theory, we can only describe *sharp* situations, which are, situations whith a sharp boundary between elements having a certain property and other elements. But, we have to deal with *unsharp* imprecise situations in which it is difficult to find a boundary. The best tool to handle the mentioned uncertainties represents the *fuzzy set theory*, originally described by Zadeh [7]. Like numerical variables take numerical values, in fuzzy logic, linguistic variables take values which are words (linguistic terms) with associated degrees of membership in a set. Fuzzy sets F, like *the density of snails is low*, which have unsharp boundaries, are well characterized by a function that assigns a real number from the closed interval from 0 to 1 to each element u in the set U. This function $\mu_F : U \to [0, 1]$ is called a membership function and describes the degree with that an element $u \in U$ belongs to the *fuzzy set* F.

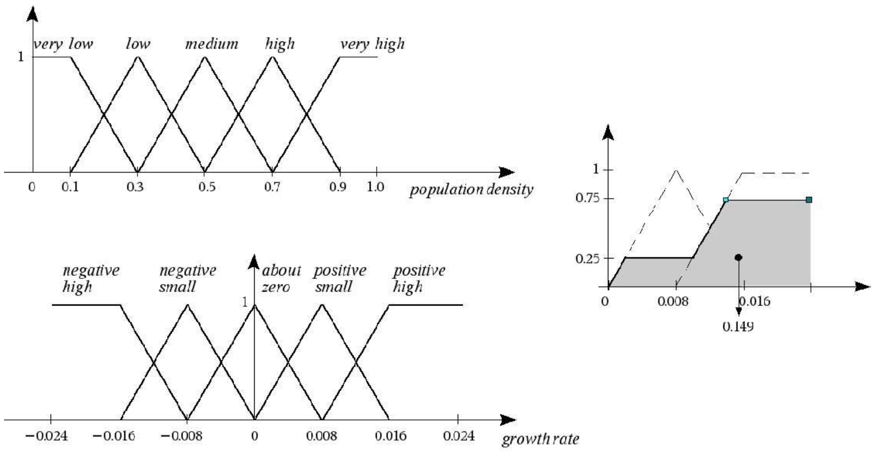

Figure 3: Definition of fuzzy sets and rules to describe the relations between different populations and model parameters

Starting from the definition of fuzzy sets for all considered variables, the principles of fuzzy-control are used to apply the rulebase in every cell of the Cellular Automaton. In the *fuzzification process*, membership functions $\mu_F : U \to [0, 1]$ are defined, which specify the degree with that a value $u \in U$ belongs to the fuzzy set F. In the *inference step*, these fuzzy terms are analyzed according to the rulebase and an output fuzzy set is generated. Then the output fuzzy set is transformed into a crisp numerical value (e.g. the growth rate of a population) by a *defuzzification* procedure. The knowledge about the relationships and dependencies between the state variables can be represented as simple rules. Two possible rules, which describe the predator-prey behavior between snails and algae, are exemplified as follows:

R_1: **if** the quantity of algae in a specific cell is *high* and the quantity of snails is *low*,
then there is a *high* likelihood that the number of snails in this cell is increasing.

R_2: **if** the quantity of algae in a specific cell is *medium* and the quantity of snails is *very high*,
then the growth of the snail population is *very low*.

Rules like these can be achieved from the relationship graph illustrated in figure 2.

5 Coupling with a finite element flow model

In the following section we will describe in detail the direct coupling of the discrete Cellular Automaton and a continuous finite element flow model and show possible transfer strategies between these two totally different model paradigms. The fundamental differences between both models require special and suitable methods. Obviously, only a holistic consideration and modeling of biological and non-biological processes leads to reliable results. Both directions have to be considered. On the one hand, the hydrodynamic conditions represent an important effect on the growth of organisms and on the other hand, the natural cover affects the local hydro- and morphodynamic. This could lead to a changed turbulence behavior and flow resistance. Especially the sensitivity of the watersubsurface to erosion is primarily effected by the existence of animals and seaweeds.

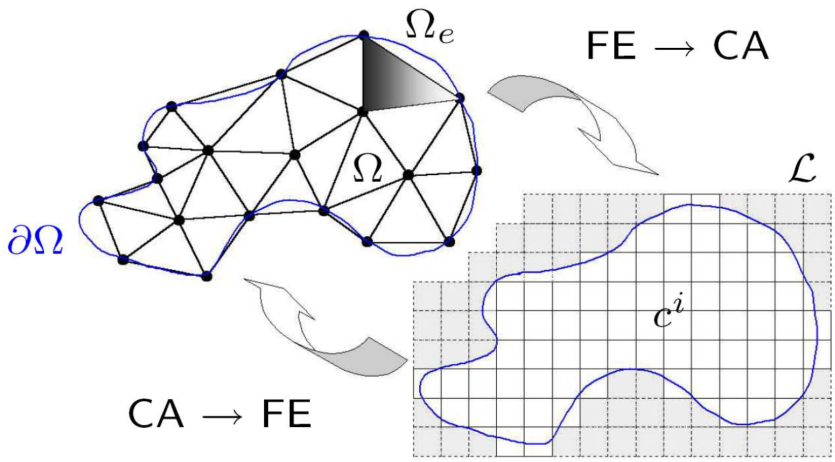

Figure 4: Coupling between a FE-Discretization and a regular lattice

A depth-integrated stabilized finite element flow model (see [5]) is the basis for the calculation of the hydrodynamic values. FEM provides a piecewise approximation of systems of partial differential equations over a continuum. In order to solve the problem, we must divide the domain Ω into a large number of elements, each of them with a simple geometry (e.g. triangles). A finite element Ω_e is a discrete piece of that continuum. All elements are connected together by nodes p_k, located at their edges. The hydrodynamic values $(v_x, v_y, \eta$ and $z)$ are determined at these nodes.

Processing of continuous simulation results in the cellular automaton

The use of these different model concepts dictates that we need an approach to interpret the continuous values of the flow model in the rules of the discrete Cellular Automaton. Otherwise, the discrete values have to be transferred into continuous parameters for a processing in the finite element model. To handle this, one or more reference elements are dedicated to each cell of the lattice. During the simulation, the hydrodynamic values can be obtained from the referenced nodes at every time step. These values describe the local hydrodynamic behavior in each cell and are used in the fuzzy rules of the CA to compute the state variables of the next time step. Thus, the whole finite element mesh can be mapped to the regular lattice of the Cellular Automaton (see figure 5).

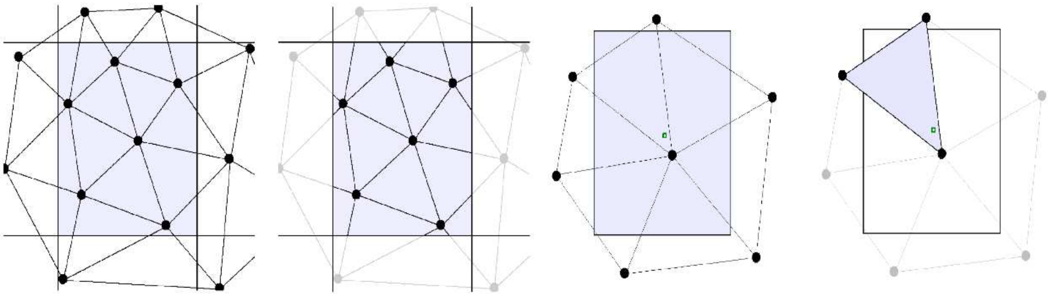

Figure 5: Mapping parts of the finite element mesh to the cells of the lattice

Processing of discrete ecological parameters in the FE-model

Populations and seaweeds affect the hydro- and morphodynamic and may not be neglected. The dense carpet of leaves acts as additional roughness and is able to raise the flow resistance. Seagrass is a very flexible material with a low flexural stiffness. According to [6], the total flow resistance F_R of the seaweeds can be obtained as the sum of the two force components F_D and F_S. F_D denotes the vertical pressure and F_S the friction force, which acts on the surfaces of the leaves. Both forces are resulting from the movement of the water around the seagrass and both are depending on the actual flow behavior.

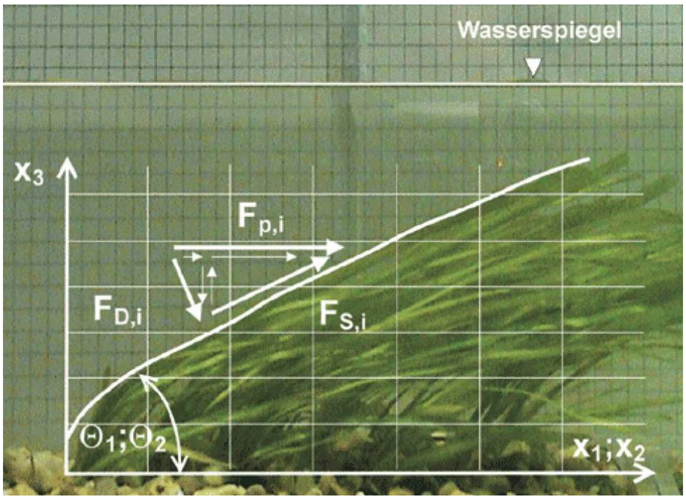

Figure 6: Resistance forces caused by the leaves of seaweeds (see [6])

With change of the seagrass variable in the cells of the CA, the friction coefficients have to be adapted in the flow model during the simulation. Depending on the density of the seagrass in a certain area, the Strickler friction coefficient k_{Str} is determined in each node of the finite element discretization. Every node p_k is influenced by the cells c_k in the voronoi-region $VR(p_k)$. Decomposition of the domain Ω in voronoi-regions:

$$
\begin{aligned}
D(p,q) &= \{x \in \Omega; d(p,x) \leq d(q,x)\} \\
VR(p,S) &= \bigcap_{q \in S \setminus \{p\}} D(p,q)
\end{aligned}
$$

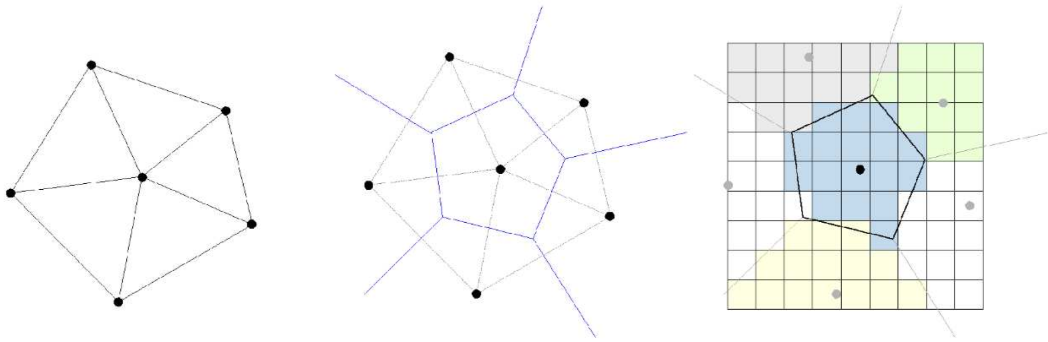

Figure 7: Voronoi-regions for the coupling between the CA-lattice and FE-mesh

6 Simulation results

First qualitative studies analyze the evolution of seaweeds in the area around the island of Sylt (Northern Germany). The simulation started with a stochastic distribution of seagrass, snails and algae. After a simulation period of two years, a typical organization of populations and seaweeds in the considered area was achieved. No seagrass and snails can be found in cells were tidal currents and wave action are strong. High concentrations of seagrass and snails only arise in cells with low flow velocities and medium water depths. Especially the complex interaction between algae, snails and different flow conditions is quite well reproduced by the model.

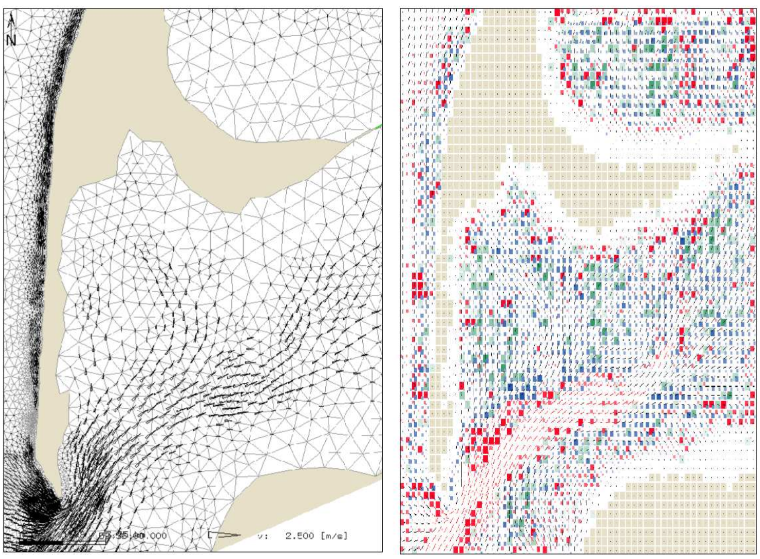

Figure 8: Hydrodynamic and ecological simulation results

Due to the evolution of the natural cover in the considered area, changes of the hydrodynamic conditions occurred. The left side of Figure 9 shows regions with seaweeds. This leads to the change of friction coefficients in these regions. The right side of Figure 9 presents velocity differences due to the consideration of seaweeds in the numerical model. These first simulations show the general influence of ecological components to the hydrodynamic model and vice versa.

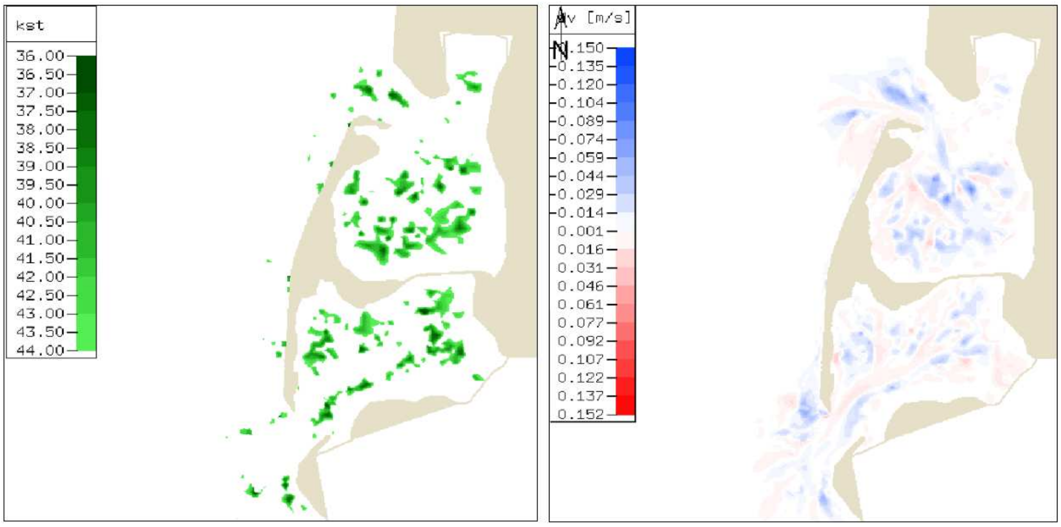

Figure 9: Friction coefficients and velocity differences due to the existence of seaweeds

7 Asynchronous parallel scheme

A Cellular Automaton based model can be effectively simulated on a parallel MIMD architecture. Assume for now that we are working with a parallel computer with p processors $P_1, \dots, P_p$ $(p \leq m{\cdot}n)$ and associate a block of components $J_j \subseteq \{1, \dots, m{\cdot}n\}$ with each processor P_j. The parallelization can be performed by dividing the lattice of cells into portions of equal size and assigning each portion to a different processor P_j. Figure 10 shows the data decomposition used for a 6×12 lattice. Unfortunately, due to this decomposition some cells are arranged on partition boundaries. Therefore, some *ghost-cells* are added to each sub-domain Ω_j. The ghost-cell technique (see [1]) is illustrated in figure 10.

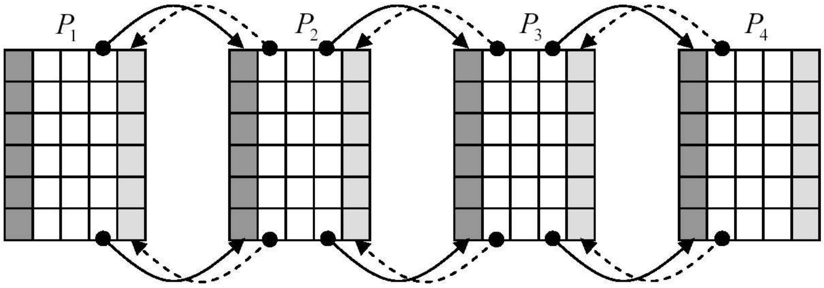

Figure 10: Data decomposition and implementation of the ghost-cell technique

Every processor sends its first and last column to the previous and following processor, respectively, and receives the last and the first column from the previous and following processor, respectively. In this way, the ghost cells are updated by the communication phase executed at each time step, and each sub-domain can be considered completely independent. Because of the inhomogeneity in the majority of physical or biological systems and different computation times, some processors finish their task much earlier than others, and the waiting time (also called *idle time*) degrades the performance of the algorithm. In a synchronized execution scheme, each processor has to wait for all the other components to be updated before starting the next computation step.

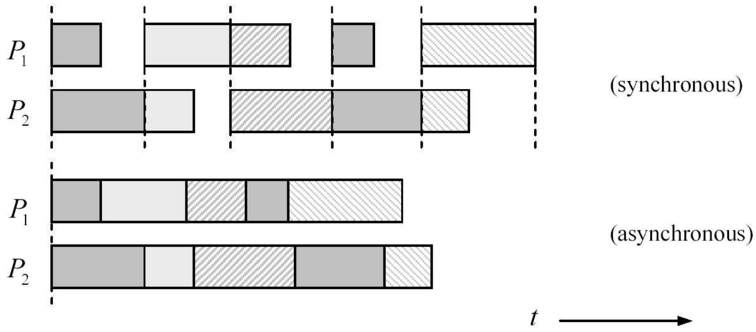

Figure 11: Synchronous vs. asynchronous computation scheme

In Figure 11, the white areas between two consecutive computations are idle times. Thus, the performance of a synchronous algorithm is largely affected by communication and the slowest process. It is well known that synchronization and communication delays are the major sources of performance degradation of synchronous parallel algorithms. Asynchronous execution, on the other hand, allows processors to continue computation without requiring them to wait for all other components to be updated. The idea of *event-oriented asynchronous methods* is to avoid processor idle time by eliminating as much as possible synchronization points. A process can work on its *own* data or on the data already received from its neighbours to proceed with the computation of the next computation step. Depending on the arrival of computed cells of the neighbours, there are different updating sequences possible for each domain.

8 Conclusions and outlook

In this paper, we presented a discrete ecological model based on a Cellular Automaton. The direct coupling between the CA and the finite element flow model poses a particular challenge. Possible transfer strategies are shown which allow holistic simulations. First simulations show possible effects and influences between hydrodynamic variables and ecological model components. Furthermore, we discussed a parallel implementation and the behavior of asynchronous parallel Cellular Automata. The asynchronous computation scheme might constitute an original alternative to load balancing in order to minimize the idle time of processors for optimizing the throughput of parallel computing resources. Future work could focus on improvements of the introduced coupled hydrodynamic and ecological model, on the refinement of the numerical algorithms as well as on extending the model for simulating long time periods.

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