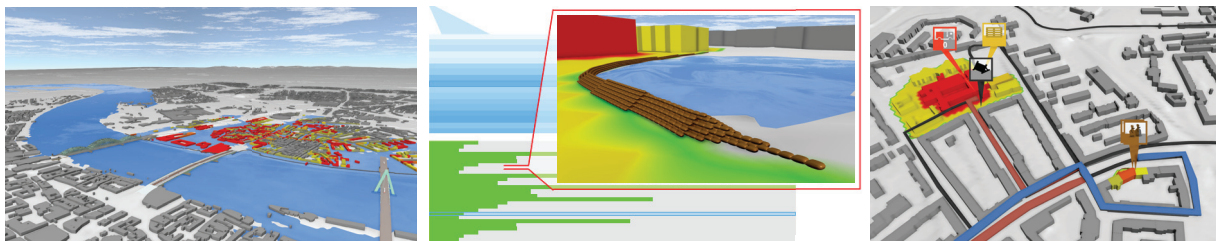


# Many Plans: Multidimensional Ensembles for Visual Decision Support in Flood Management

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**Figure 1:** Making many plans for multiple flood scenarios. (Left) Overtopping incident. (Middle) Scenarios are modelled as multidimensional, time-varying simulation ensembles, managed by Continuous World Lines. A zoom lens displays details about an optimized water barrier which protects a prioritized area. (Right) Visualization of plan logistics and construction.

## Abstract

Uncertainties in flood predictions complicate the planning of mitigation measures. There is a consensus that many possible incident scenarios should be considered. For each scenario, a specific response plan should be prepared which is optimal with respect to criteria such as protection, costs, or realization time. None of the existing software tools is capable of creating large scenario pools, nor do they provide means for quick exploration and assessment of the associated plans. In this paper, we present an integrated solution that is based on multidimensional, time-dependent ensemble simulations of incident scenarios and protective measures. We provide scalable interfaces which facilitate and accelerate setting up multiple time-varying parameters for generating a pool of pre-cooked scenarios. In case of an emergency, disaster managers can quickly extract relevant information from the pool to deal with the situation at hand. An interactive 3D-view conveys details about how a response plan has to be executed. Linked information visualization and ranking views allow for a quick assessment of many plans. In collaboration with flood managers, we demonstrate the practical applicability of our solution. We tackle the challenges of planning mobile water barriers for protecting important infrastructure. We account for real-world limitations of available resources and handle the involved logistics problems.

## 1. Introduction

The standard workflow of disaster management can be regarded as a cycle consisting of two phases. In the first phase (planning), actions are defined for mitigation. In the second phase (response), the prepared plan is executed. Since the course of events can only be predicted to a limited degree of certainty, numerous alternative scenarios have to be considered. In the response phase, decision makers require quick and intuitive access to a pool of pre-cooked scenarios and associated plans [Mar08]. To our knowledge, no integrated solution exists that allows the user to create large scenario

pools and provides mechanisms to extract relevant information in time-critical situations. Our approach aims to implement the scenario pool concept as we see it: first, create many plans in the preparation phase; second, quickly pick the most appropriate one in the response phase.

The experts from the Flood Protection Center of Cologne provided us with an important application. The city of Cologne is currently protected with more than 11 kilometers of mobile walls. However, they are only effective up to a certain water level. If the water level is too high, overtopping happens (Figure 1, left). The emergency plan then as-

sumes the evacuation of the flooded area and protection of important infrastructure objects with temporary water barriers. The predictable nature of overtoppings is essential for the feasibility of our approach. The crucial characteristics of overtoppings such as starting time, duration and peak water level can be usually forecasted up to 24 hours in advance. This gives to the city services time to execute an appropriate protection plan. In the light of a high variability of overtopping parameters and considerable prediction uncertainty, it is important for the management officials to have a large pool of pre-cooked plans. According to the situation at hand, they can pick the one which is optimal with respect to a set of parameters such as plan realization time or estimated costs. Providing means to create, access, and analyze such pools is the main goal of this paper.

The domain experts claim that scenarios are needed for different peak water levels, overtopping start times, and durations. Additionally, they want to try various combinations of barriers of three different types placed in many possible locations. This defines two classes of simulation ensembles: the first one is essentially incident ensembles, and the second one can be regarded as ensembles of protective measures. Based on this, we formulate our first subgoal (S1) as providing scalable visual tools to manage multidimensional, time-dependent ensembles. Transporting materials to appropriate locations and constructing barriers takes considerable time. Hence, it is important that the planned protective measures can be implemented before the overtopping actually starts. Depots should be stocked with barrier construction materials in advance to fulfill the needs of protection plans. Additionally, one needs to account for the costs of materials and cargo containers used, as well as the costs of trucks freight and fuel. Our second subgoal (S2) is then to provide the decision makers with assistance in logistics by addressing the above issues.

To our knowledge, existing solutions in the disaster management area are not capable of solving the whole set of problems defined. Most of them are aimed at plan coordination during the response phase. Moreover, previous approaches are not scalable with respect to multidimensional ensembles. We suggest a solution that integrates scalable multidimensional ensemble simulations and logistics optimization with rich visualization capabilities (Figure 1, middle). We provide views where users can see how exactly the protection plans should be executed in order to obtain the expected results (Figure 1, right). In realization of our approach we take advantage of Visdom [vis], a modular framework capable of controlling, visualizing, and analyzing multiple simulation runs. In summary, this paper contributes the following:

- Continuous World Lines, a scalable interface for managing multidimensional, time-dependent ensembles
- Combinatorial ensembles to speed up the creation of many protection alternatives



**Figure 2:** Area of interest protected by mobile walls. If overtopping happens, vital infrastructure should be kept water-free. The importance of objects is outlined by user sketches, coloring buildings and areas according to user-defined priorities between 0 and 1.

- Integration of GPU-based cloud simulation, logistics computation, and web services
- Automatic optimization of barrier characteristics based on rough user sketches and simulation results
- Visual techniques facilitating the selection of the right plan according to protection, realization time, and costs
- Interactive, time-varying visualization of resource delivery plans and barrier construction progress

## 2. Related work

There is a consensus that both phases in the disaster management cycle could benefit from information technology [CoUITtEDM05]. However, most of the available tools are designed for plan coordination during the response phase only [TRW\*07, Mar08, GWL07]. SeCom [Sec] is a serious game where users manage a flood in an urban area. For geospatial action planning, the user has to cope with a huge amount of heterogeneous data to evaluate the options [AAJ\*07]. SoKNOS [DPZM09] is a semantic technology-based approach to access and structure information from various sources. RimSim [Cam10] is a software tool that allows the user to create incident scenarios and training responses. Malik et al. [MMME11] describe a visual analytics process for resource allocation and risk assessment in a maritime context.

Ensemble simulations facilitate the exploration of parameter spaces and help to tackle input uncertainty. Torsney-Weir et al. [TWSM\*11] use ensembles to sparsely sample the parameter spaces and guide the user through the cycle of fine-tuning a segmentation algorithm. Vismon [BMPM12] is a tool for fisheries decision making equipped with powerful mechanisms for exploration of the output of ensemble simulations. Coffey et al. [CLEK13] present an approach to inverse design via direct manipulation on the visualization of ensemble simulation results. Time-dependency requires spe-

cial attention in information visualization [AMST11]. However, this aspect is not yet covered with respect to multidimensional ensembles.

A set of fundamental visualization techniques that can be used for simulation in production and logistics has been presented as a taxonomy by Wenzel et al. [WBJ03]. Heydekorn et al. describe an interactive visualization of a logistics scenario [HNDN11]. In the context of our application scenario, geo-referenced visualizations are of particular interest. Barcelò et al. [BGP07] use street map visualizations of transportation data. Tominski et al. [TSAA12] propose the in-situ visualization of 2D-trajectories as stacked bands with attributes encoded by color. Krüger et al. [KTW\*13] present a technique for interactive query-based trajectory filtering.

Some aspects of decision support in flood management were addressed in the authors' previous works. World Lines [WFR\*10] is an interactive visualization for controlling parallel simulation runs. However, in case of many alternative runs, its workflow slows down considerably. Enhancement towards simulation ensembles [WRF\*11] had a limited scalability, especially with respect to multiple dimensions. Further research dealt primarily with sketching boundary conditions [RWG\*12] and visual analysis of local features aggregated over multiple time steps [RWF\*12] and did not address the above issues.

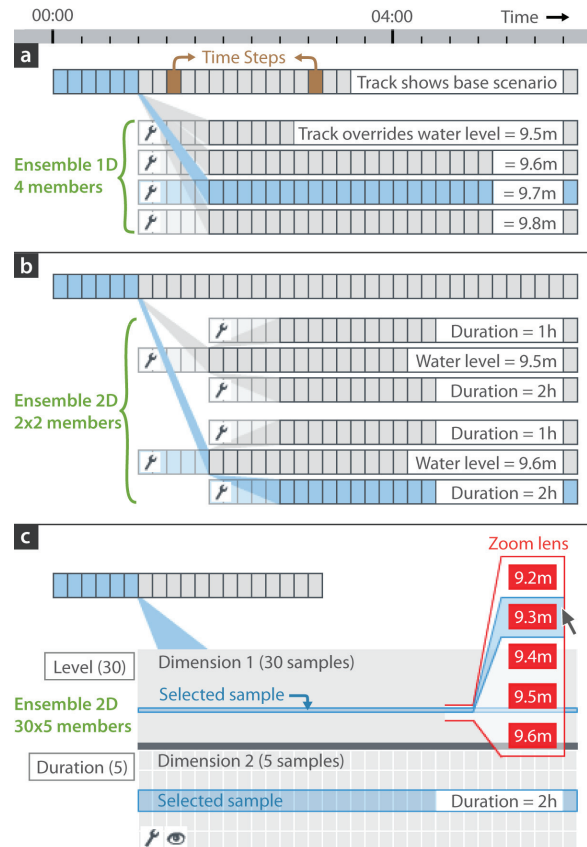
### 3. Interactive prioritization

The structure of the following sections is inspired by the user's typical workflow necessary to set up the tool and solve the given problem. The user starts with picking the domain of interest and marking the important areas. In our case, the domain corresponds to an urban area of Cologne (Figure 2). The areas of special importance are identified using an interactive prioritization mechanism. The domain is marked out with sketched lines, and priority values between 0 and 1 are assigned to the resulting areas. The assigned priorities are visualized with colors. Scenarios where the highly prioritized areas end up being flooded are undesired and thus will be ranked lower in the resulting pool. From now on, we refer the reader to the video that demonstrates the interactive features [man].

In the considered domain, our collaboration partners have identified several infrastructure objects that require special attention if the primary flood protection of the city (i.e., the mobile walls) was to fail. As shown in Figure 2, these are the city hall and, especially, the subway entrance nearby; the hospital, particularly the emergency rooms location; and one more subway entrance close to the river.

### 4. Managing multidimensional time-dependent ensembles

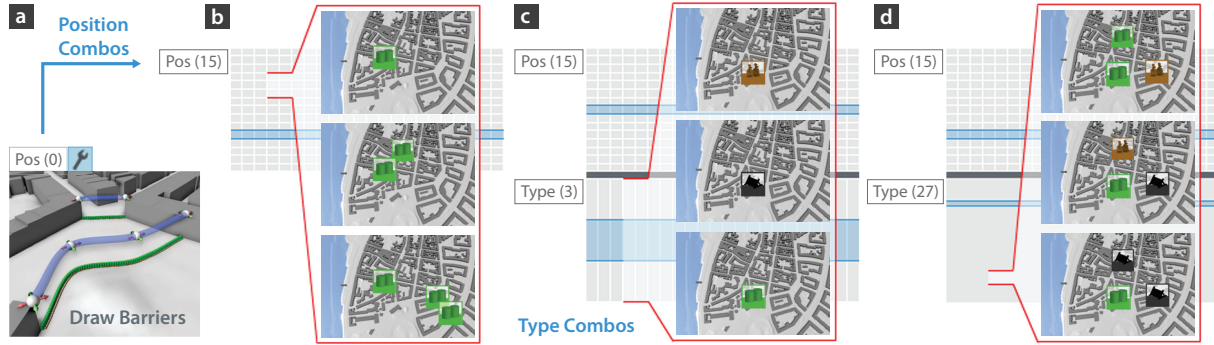
On the next step, the user creates the flood simulation ensembles. Ensemble simulations are needed when the user has



**Figure 3:** Visual ensemble management. (a) 1D-ensemble of four water levels created by branching. The chosen scenario is highlighted in blue. (b) Scalability issues as soon as another dimension (overtopping duration) is added. (c) Continuous WL display a 2D-ensemble consisting of 150 members. A zoom lens simplifies the selection of members.

little or no information about some of the simulation parameters. In this case, ranges of parameters are sampled according to certain distributions. Ribičić et al. [RWG\*12] utilize ensemble simulations of levee breach scenarios to handle the uncertainty in breach positions, breach widths, and water levels. They make use of the World Lines (WL) interface.

In WL, every simulation run (or scenario) is represented as a track which is essentially a sequence of time steps (Figure 3a). At any time step, it is possible to override some set of simulation parameters, thus creating a new track that visually originates from the base track. This is referred to as branching. Branching creates a tree of tracks sharing the same time axis. To choose a certain scenario, the user has to find the right path through the tree. WL highlight this path to emphasize the related parameters (see blue highlighting in Figure 3a). The WL interface has been extended to study parameter spaces by creating ensembles for intervals and distri-



**Figure 4:** *Combinatorial ensembles. (a) Based on multiple user sketches, the system (b) generates an ensemble of barrier positions containing all possible combinations, indicated in zoom lenses. (c) Added dimension for barrier types. (d) Depending on the selected position combination, a different number of type variations is possible and displayed.*

butions [WRF\* 11]. Families of simulation runs were created for varying parameter values. Each parameter variation in an ensemble is called an ensemble member. Figure 3a shows an ensemble with four members for different water levels.

The WL approach to ensemble handling reaches its limits as soon as the user decides to add another dimension, the overtopping duration, to the existing 1D-ensemble of water levels. First, adding a dimension would require manipulating every member of the initial ensemble, which is time-consuming. Second, visualizing the resulting tree of tracks creates a lot of clutter even for two dimensions. This makes ensemble member selection a difficult task, since the user has to find the right path in the tree (Figure 3b).

#### 4.1. Continuous World Lines

We present a novel approach to creating, visualizing, and navigating multidimensional, time-dependent ensembles: Continuous World Lines (CWL). The essence of the approach is that the tracks are reordered to group dimensions together (Figure 3c). This leads to a more compact representation while retaining the temporal layout useful for progress monitoring, time navigation, and visualization of time-dependent properties.

To specify a member of an  $n$ -dimensional ensemble, one needs to define a tuple  $(x_1, \dots, x_n)$  of samples. Therefore, instead of clicking a single track, the user has to specify a sample for every dimension. This can be done by clicking into ensemble dimension representations. The corresponding sample for every dimension is highlighted in blue, as in Figure 3c. This approach does not allow the user to visualize several ensemble members at once if they share samples. One solution to this problem is to employ color-coding.

If many values are sampled in some of the ensemble dimensions, the visualization becomes continuous and turns into a band rather than a stack. This may cause problems

with selecting samples for this dimension. To tackle this, we implement zoom lenses, a user interface feature that expands a condensed region in a pop-up side view so that different samples are clearly distinguishable. In this view, the corresponding samples are labeled to ease the navigation. In Figure 3c, the user has selected the ensemble member corresponding to the scenario where the overtopping lasts for 2 hours and has the peak water level of 9.3 meters.

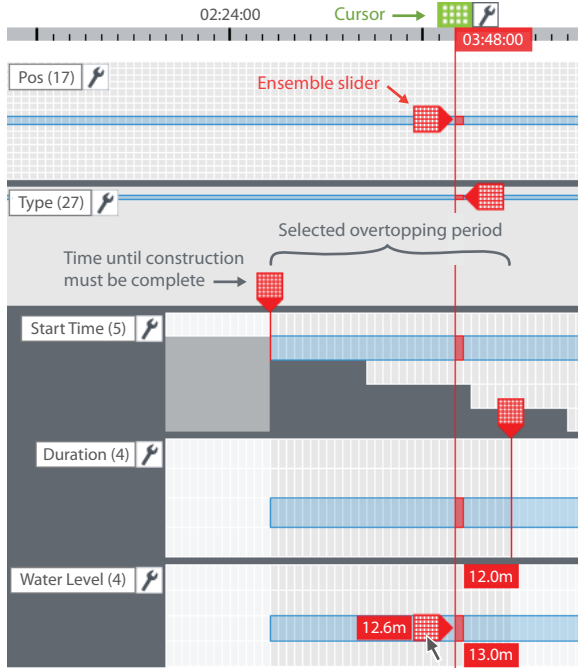
#### 4.2. Combinatorial ensembles

For every member of the 2D-ensemble previously discussed, the domain experts want to try multiple alternative mitigation measures. The Flood Protection Center of Cologne uses three different types of barriers, namely, sandbags, AquaRiwa [Aqub], and AquaBarrier [Aqua]. The experts would like to test water barriers of all types placed at various locations.

With the previous approach, tracks would have to be manually created for each combination of barrier locations. Since the number of combinations to try for  $n$  locations grows exponentially as  $2^n$ , creation of so many scenarios would be tedious. We propose a combinatorial ensembles approach to speed up this workflow. The user defines the search space by sketching into the scene rendering all barrier locations that might be useful to protect the important infrastructure (Figure 4a). The framework then creates scenarios for all possible combinations (Figure 4b). The search space is cut by dropping barrier locations that the water can not reach even in worst-case scenarios. These locations are identified using a fast filtering procedure that propagates a constant, high water level across the domain.

The next ensemble dimension to add is the barrier type. Type variations do not influence the simulation, but affect construction times and protection plan costs. For  $m$  possible barrier types and  $n$  user-defined locations, the number of





**Figure 5:** 5D-ensemble from the case study showing the two protection dimensions and the three incident dimensions. The time-navigation cursor is equipped with a slider for each dimension to enable interactive browsing through ensemble members.

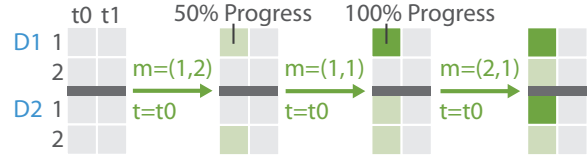
ensemble members sums up to

$$(m + 1)^n = \sum_{i=0}^n \binom{n}{i} m^i = \sum_{i=0}^n k_i^{m,n}$$

For  $i$  barrier locations in use,  $k_i^{m,n}$  type combinations can be selected. The CWL visualization takes this into account by dynamically adjusting the number of samples for barrier types depending on which combination of locations is chosen. In Figure 4c, the user has selected a sample corresponding to only one barrier position, which gives him three type samples to choose from. In Figure 4d, the selected sample contains three possible barrier positions, hence there are  $3^3 = 27$  possible type combinations. Note that for combinatorial ensembles, the zoom lenses display thumbnails. They contain a view from above supplemented with icons to indicate barrier locations and types.

### 4.3. Temporal ensembles

The last ensemble dimension to add is the overtopping start time. As it would come naturally in case of branching at different time steps, every sample for this temporal ensemble is shifted along the time axis. The resulting side effect is a distinctive stair-like pattern in the visualization of this dimension. The pattern is clearly visible in Figure 5, which shows



**Figure 6:** Progress visualization in an ensemble with dimensions  $D1$ ,  $D2$ , and time steps  $t0$ ,  $t1$ . The green arrows denote the incoming progress for a finished simulation step, identified by the member  $m$  and a time step  $t$ .

the complete 5D-ensemble of simulations the user creates for solving our problem. The selected start time sample corresponds to the second earliest overtopping start. Notice that there is no such pattern for overtopping durations. The reason is that the flooding continues even after the overtopping is over, and thus has to be simulated further on.

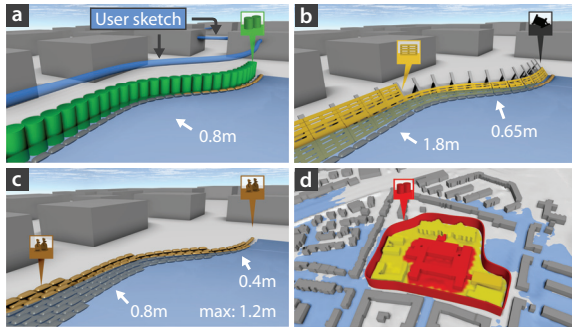
### 4.4. Navigation with cursors and sliders

Temporal navigation is crucial given the time-dependent nature of simulations, and the CWL interface features an extensive support for it. An interactive time cursor provides a clear indication of the selected time step that is shown in all linked views (Figure 5). The cursor supports dragging along the time axis and displays the current time in a label.

For selecting an ensemble member, the user has to fully specify the samples tuple corresponding to the ensemble dimensions. One way of doing this was described earlier in this section and involved click-based selection of samples from the ensemble dimensions. As an alternative, the user is provided with a set of interactive ensemble sliders, one for each ensemble dimension (Figure 5). If an ensemble slider is moved, it displays the current sample the same way as zoom lenses do. Additionally, for numeric parameter ranges, the minimum and maximum values are displayed in labels. Notice that the two temporal ensemble sliders are oriented horizontally. This better relates them to the time axis. A convenient implication is that the two sliders for overtopping start time and duration match the time extent of the flooding.

### 4.5. Cloud simulation and progress monitoring

In our setup (Figure 5), the number of barrier position combinations to try is  $2^5 = 32$  in total and 17 after the filtering procedure has been applied. Adding the type dimension, this leads to 195 plans overall. The total number of scenarios to simulate is  $17 \times 4$  durations  $\times 4$  levels = 272. We point out that barrier types and start times do not affect the simulation, but influence the logistics computations. Hence, they do not need to be simulated. The overall ensemble size is then 195 plans  $\times 5$  start times  $\times 4$  durations  $\times 4$  levels = 12480. We use a GPU-based flooding simulation based on



**Figure 7:** Barrier heights vary locally depending on the barrier type and simulated water depth. Colored labels denote delivery locations for the required materials. (a) AquaRiwa (green). (b) AquaBarrier (black) with a second row of pallets (yellow) if needed. (c) Sandbags (brown) using pyramid stacking. (d) Red walls indicate protection failure due to overly high water levels.

the shallow-water method [BSA12]. To speed up the simulation of multiple scenarios, our framework supports cloud execution. Our case study required 8 hours of simulation on 5 PCs (Intel Core i7-3770, 16GB RAM, GeForce GTX 680).

To visualize properties in CWL, we map values onto samples (see Figure 3). If the values are time-dependent, we map them according to the time axis. For progress visualization, we have to map completed simulation steps. Each step is defined by an ensemble member  $m$  and a time value  $t$  (Figure 6). Since a member  $m$  corresponds to a samples tuple, all these samples have to be updated when the simulation step is complete. Figure 6 shows three progress updates of a 2D-ensemble, indicated by green arrows. In step one, the member (1,2) has simulated the first time step  $t_0$ . Two samples are affected: sample 1 in the first dimension  $D1$  and sample 2 in the second dimension  $D2$ . Both samples now show a progress of 50% at time step  $t_0$ . The next update completes the progress for sample 1 in  $D1$ , since the tuples (1,  $i$ ) have now been completed for all possible  $i$ .

## 5. Logistics

In both phases of the disaster management cycle, it is important to have a clear understanding of the response plans. Enough materials should be available in depots to construct the barriers. Flood managers need to have a good estimate for plan realization costs and times. Efficient material transportation plans should be available for each scenario. Our tool supports flood managers in handling these issues. To compute the logistics plans, one or more buildings in the region are picked as depots. For the computation, each depot is assumed to have an unlimited amount of material of every type. Our system evaluates how they should be filled to ensure the feasibility of all scenarios from the pool. The user

Barrier Type	Cargo	Assembly	Cost
Sandbags	600	45	2
AquaBarrier	base	120	70
	pallets	130	8
AquaRiwa	330	120	126

**Table 1:** Attributes of barrier types: Number of units per cargo; Assembly time per unit per person (s); Cost per unit (€). AquaBarrier may include two material types.

can select the number of trucks starting at each depot. This does not strictly bind each truck to its depot, but rather defines the overall number of trucks operating in the area.

### 5.1. Barrier height adjustment

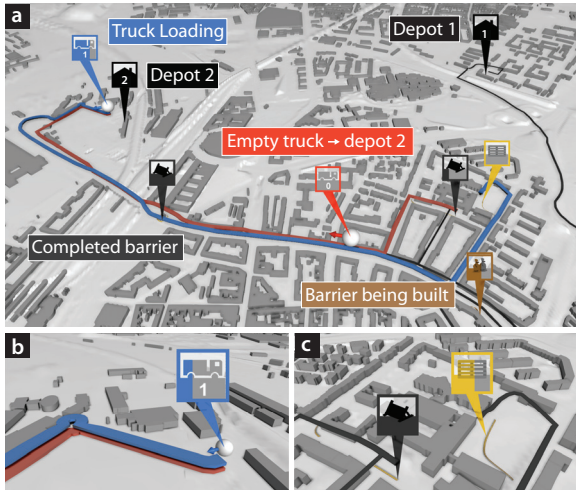
In our previous approach, water barrier heights were defined by the user. Now the framework automatically derives them from the simulation results (Figure 7). The barrier heights are set locally according to the simulated water depth. Possible barrier heights depend on the type. Figure 7a shows an AquaRiwa barrier placed along a user-sketched line. AquaRiwa holds up to 0.8 m of water. AquaBarrier (Figure 7b) is only effective up to 0.65 m if used in one row. If a higher water level has to be handled, fiber glass pallets can be put on top, making the barrier capable of holding 1.8 m of water. Sandbags can be stacked in a pyramid manner, thus covering the range from 0.2 m to 1.2 m depending on the pyramid height (Figure 7c). If the water level at a location is too high, a failure indication is displayed (Figure 7d).

The height adjustment mechanism is a convenient optimization for construction materials consumption. One more implication is that barrier options can now be sketched *through* buildings, since the system will never use superfluous parts of the sketches (see Figure 7a). This makes sketching more convenient, because the user does not need to snap the ends of sketched lines to the walls of buildings.

### 5.2. Cargo types and barrier characteristics

In our discussions with the experts, it was pointed out that the currently used barrier types constitute two cargo classes. For the first class, construction materials are packed into drop-off containers. A truck is able to carry one container at a time, hence it returns to a depot after each container is delivered. Materials of the other class are treated per-unit. The main implication is that after unloading the required number of material units at one destination the truck can go to another destination if there is leftover material.

Every barrier type is characterized with a set of attributes listed in Table 1. From the three barrier types listed, only AquaRiwa is treated per-unit. The other two types are pre-packed into drop-off containers. We assume that every con-



**Figure 8: Logistics visualization.** (a) Labels display the truck positions and delivery destinations. Colored lines indicate the current route for each truck. (b) Overlapping routes are stacked. Progress bars in labels show the status with respect to (b) truck loads or (c) construction status.

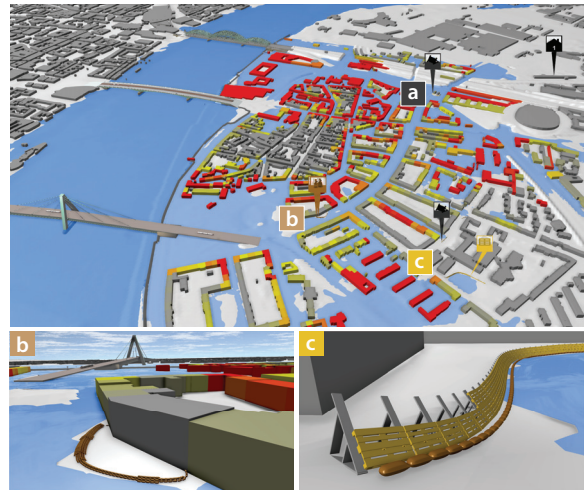
tainer is loaded and unloaded in 300 seconds. AquaRiwa takes 60 seconds per unit per person to load or unload.

### 5.3. Computation and output

In our application, we encounter an instance of a so-called Capacitated Vehicle Routing Problem (CVRP), where a number of destinations scattered in the region of interest must be serviced by a fleet of vehicles of a known capacity [DR59]. Being an NP-hard problem, CVRP is usually tackled using integer linear programming with some sorts of heuristics employed for larger instances [FLdA\*04].

For every barrier, we compute one or more logistics destinations, i.e., locations where trucks should deliver materials. These destinations are displayed as labels in 3D (Figure 7). We regard any truck trip (depot-destination, destination-destination, or destination-depot) as a logistics event associated with a quantity and type of the cargo aboard. The duration of an event is calculated using Table 1 and the travel times between locations. Timings and trajectories are retrieved from a public *OpenStreetMap* routing service.

Using the above concepts, our logistics problem can be formulated as finding the “optimal” sequence of events to satisfy the demands of all logistics destinations. The optimization criteria are plan realization time and costs. For solving the problem, we have implemented a brute-force solver with backtracking. However, this approach can only handle relatively small problem instances. For larger ones, we employ a greedy heuristics that at every step picks the event that would finish sooner. Main outputs of the logistics



**Figure 9: Important infrastructure protected from flooding using the chosen plan from Figure 8.** (a) AquaBarrier and (b) sandbags at the subway stations. (c) AquaBarrier supplemented with pallets protects the hospital.

module are the distribution plan, barrier construction time, overall costs, and the required material quantities per depot.

The costs are computed as  $C_{tr} + C_f + C_{cont} + C_{mat}$ . Here,  $C_{tr}$  corresponds to the costs for the trucks freight and depend on how many hours each truck has been in use (€50 per truck per hour).  $C_f$  are the fuel costs, computed from the lengths of the trajectories.  $C_{cont}$  is the total price of all cargo containers required (€6000 per container). The costs of the consumed materials are given by  $C_{mat}$ .

### 5.4. Visualization

The clear representation of computed delivery plans is important due to the presence of multiple spatio-temporal components. Trajectories of trucks may carry important information. For instance, multiple trajectories passing through the same street mean a particular importance of that street for the plan realization. If the street gets blocked by construction works or a traffic jam, the plan might be no longer possible to finish in time. However, in-situ rendering of multiple trajectories creates visual clutter. Moreover, it does not answer other questions the user might ask, e.g., “What is the delivery schedule for truck X?” or “When is barrier Y completed?”.

We solve the above issues by providing a visualization of delivery plans that combines interactive navigation with 3D-animation. The time aspect is captured by the cursor of CWL. For any selected time step, the system calculates the corresponding positions of the trucks and renders them schematically into the 3D-model of the city (Figure 8a). The past and future trajectories of the trucks are rendered in black, while the current delivery route of each truck is dis-

	Protection [0-1]	Costs [k€]	Construction Time [hh:mm]	
	Adjust weights →		→	
1	0.95	31.5	00:40	
2	0.96	41.2	00:50	
3	0.93	33.6	00:45	Active plan
4	0.93	39.5	00:45	
5	0.96	44.9	02:56	
⋮				
12	0.86	---	---	Water level too high
13	0.86	71.0	08:01	Cannot be built in time

**Figure 10:** Visual ranking of plans according to their performance in the chosen incident scenario. The rank is computed as a weighted sum of the qualities with respect to protection, costs and construction time. The user has selected the plan (blue) which is visualized in Figures 8 and 9

played in a color assigned to that particular truck. If some of the displayed trajectories have overlapping fragments (e.g., when two or more trucks pass through the same street in a short time span), we stack these trajectories in the vertical direction in a way that each of them is visible (Figure 8b).

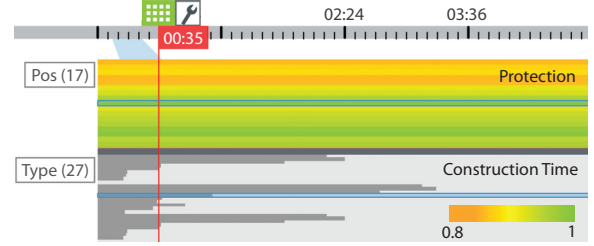
Labels encode important information. Each truck is provided with a label showing an icon with the corresponding cargo type and a progress bar. It changes state when the truck is loading or unloading (Figure 8b). Other labels indicate the barrier types at logistics destinations and the construction progress (Figure 8c). By moving the CWL cursor ahead, the user can observe the course of the flooding (Figure 9a). The user can navigate the 3D-view to see the visualization of building damages or check out the construction details of particular barriers in the selected scenario (Figure 9b,c).

## 6. Analysis and response

As soon as all the incident scenarios and protective measures are simulated, the scenario pool is complete and can be used in the response phase. Interfaces are needed to quickly assess and compare multiple response plans. If an overtopping is predicted, the flood manager enters the expected values for the overtopping starting time, duration, and peak water level, thus specifying an incident scenario to handle. Entering the worst-case values within the uncertainty range is recommended, since it leads to a more robust protection.

### 6.1. Ranking and information visualization

For the given incident scenario, the flood manager typically has a large choice of protective measures and associated logistics plans available in the pool. One way to proceed would be selecting individual protection plans and studying them in the 3D-view. However, this approach is tedious and not applicable in a time-critical situation. We suggest a ranking view that sorts plans according to their quality and displays them as horizontally stacked bars (Figure 10). The quality of



**Figure 11:** Embedded visualization in CWL ensemble dimensions. The position dimension shows the possible protection levels for the selected incident. The type dimension displays construction times for the selected position sample.

a plan is computed as a weighted sum of the values characterizing protection, costs, and construction time. Weights can be changed interactively [GLG\* 13]. If a protection plan fails due to overly high water levels or can not be implemented in time, it receives a penalty and thus ranks low in the pool. A text indicates such plans (Figure 10). The view enables selection of plans to analyze their properties in linked views.

The values  $q_p$ ,  $q_c$ , and  $q_t$  characterizing the resulting protection, costs, and construction time respectively, are displayed in the corresponding fragments of stacked bars. They are calculated as follows:

$$q_p = \frac{p - p_{\min}}{p_{\max} - p_{\min}}; \quad q_c = 1 - \frac{c - c_{\min}}{c_{\max} - c_{\min}}$$

where  $c$  denotes the costs, and  $q_t$  is defined analogous to  $q_c$ . For calculating the protection  $p$ , damage values for the buildings are aggregated. Let  $B$  be the set of all buildings, and  $BP$  the set of all buildings in the prioritized areas. Then,

$$p = (1 - \alpha) \left( \frac{\sum_{i \in B} (1 - d_i)}{|B|} \right) + \alpha \left( \frac{\sum_{i \in BP} \text{prio}_i (1 - d_i)}{\sum_{i \in BP} \text{prio}_i} \right)$$

In the above formula,  $\text{prio}_i \in [0, 1]$  is the priority value of the building  $i$ , and  $d_i \in [0, 1]$  is its damage. The damage of a building is estimated by sampling water levels at all sides. The calibration parameter  $\alpha$  is set to 0.97. Finally, the *min* and *max* values for protection, construction times and costs are calculated across all the plans in the pool.

The ranking view makes it possible to quickly identify several response plans that perform best for the given incident scenario. However, the flood manager might need a more detailed exploration of the set of possible plans. The CWL interface is capable of visualizing the values for protection, costs, and construction time on top of ensemble dimensions. Samples in one dimension display the chosen quantity with respect to the selected samples in all other dimensions. In Figure 11, every sample of the position dimension shows the protection according to the selected incident. The protection is encoded with color. At the same time, samples of the type dimension show the construction times for



the selected position. The construction time is visualized as a horizontal bar related to the time axis. Visualizing properties on top of CWL simplifies the navigation over plans if many combinations are involved. Using the color code, one can identify the regions of interest within the dense representation. Zoom lenses support a more precise selection.

## 7. Evaluation

At a dedicated workshop, which took place at the Flood Protection Center of Cologne, the experts specified their requirements for our solution. The committee consisted of two flood managers and a logistics expert. They provided valuable input concerning the specifics of flood protection in their area. The domain was picked, and the data for terrain and buildings provided. Barrier types and logistics requirements were discussed. Important infrastructure was identified to be protected in case of an overtopping. The set of considered barrier locations was picked. After running the ensemble simulation, we found out that, for the more severe incidents, less protection was possible, but the high-priority infrastructure could always be protected.

During the evaluation session, we demonstrated the workflow and the involved visualizations. Being familiar with the concept of WL, the experts agreed that creating a large scenario pool required a more elaborated interface. In this respect, the advantages of the CWL approach to ensemble creation were well understood. Navigation with the cursor, ensemble sliders, and zoom lenses was found useful and intuitive. The definition of a search space by sketching all protection options and the concept of combinatorial ensembles was well received. The interactive prioritization mechanism was found convenient, as well as the depots selection. Even though there existed multiple depots in Cologne, the experts claimed that they could use this feature to test the depots' performance or to find better locations. The ranking view was highly rated by all domain experts. They found it very intuitive and pointed out a good responsiveness with respect to adjusting the weights for re-ranking. Discussing the information visualization in CWL, construction time indication on top of samples was seen as the most useful.

Finally, the logistics computation and visualization was found very helpful. The experts asked for a similar functionality to support mobile walls construction. They highly regarded the possibility to modify the number of trucks and people working on-site and to obtain the new material distribution plans and their rankings on the fly. They also made suggestions for improvement. First, they were lacking the ability to limit the amount of materials in depots. Second, adjusting the truck routes and accounting for difficulties such as blocked roads when computing the logistics plans would be useful. Third, they could see the need for several user models suitable for different levels of technical expertise.

Relying on the experts' feedback, we conclude that our

solution reaches the goals S1 and S2 we posed in Section 1. The experts can see practical use of our tool in two cases. The first case is the preparation phase. They would like to demonstrate different alternative scenarios to the decision makers in order to better justify particular preparation steps. In the second case, during an emergency event, the experts would recall various response plans from the scenario pool, re-adjust them according to the actual transportation or human resources, and quickly re-rank them to pick the best.

## 8. Conclusions and future work

Disaster management is an important and challenging field for employing cutting edge technologies. However, having quality simulation methods and powerful computers at their disposal, humans are still unable to predict natural disasters both early and accurately. We suggest a way of handling this prediction uncertainty by following the *in omnia paratus* principle. In flood management, it means to prepare a stock of many response plans for various possible catastrophic scenarios in advance. To support this, we suggest a combination of multidimensional ensemble simulations and logistics computations with interactive visualizations.

We simulate flooding scenarios with state-of-the-art GPU-based procedures that can be performed in a cloud. However, creating large scenario pools would still require a vast amount of computation time. We could benefit from automated monitoring of simulation runs. Individual runs could be interrupted as soon as the protective measures fail. Equivalent simulation steps from different runs could be re-used.

The resource distribution plans delivered by our tool are usually suboptimal due to fast but simple algorithms. However, domain experts stress out that the robustness of a response plan is more important than plan optimization. Our logistics computation is fast enough to re-calculate on the fly. This is useful when parameters like the number of trucks or number of people working on-site are not as expected. What could be improved is depot handling. By limiting the capacity of depots, we could obtain more balanced plans in terms of resource placement, while retaining the possibility to estimate material amounts for covering multiple plans.

Our visualizations for resource distribution plans were received well, but there are shortcomings remaining. First, our animated visualizations are not scalable with respect to many trajectories. Second, having a static representation of resource distribution plans preserving the temporal aspects would be useful. Third, the domain experts ask for mechanisms for detection and avoidance of regions where traffic jams or other unwanted circumstances might happen.

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