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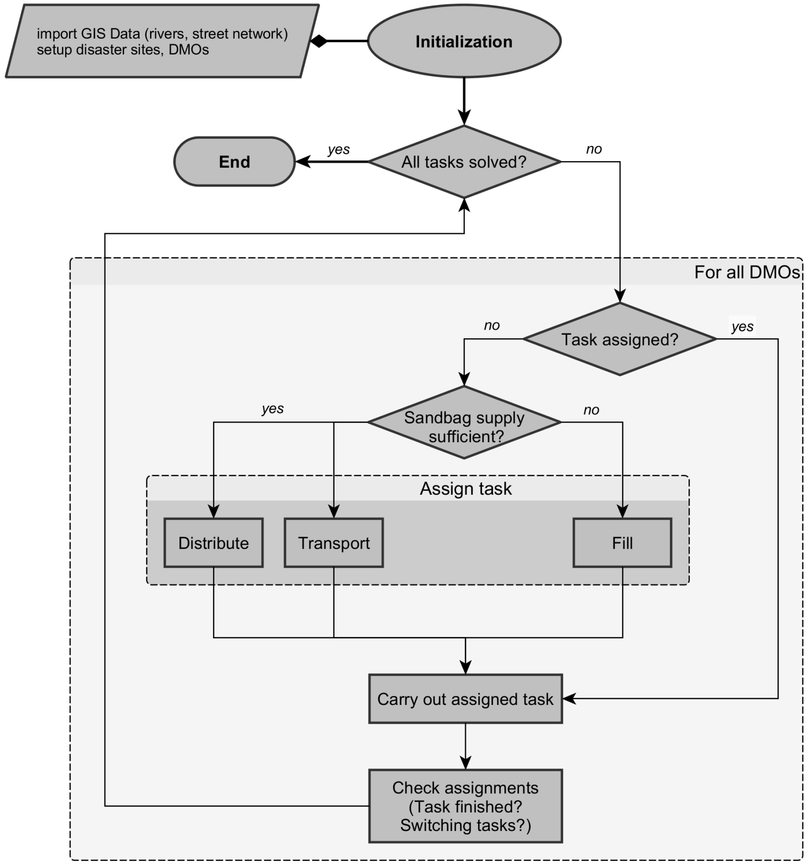
Towards thresholds of disaster management performance under demographic change: exploring functional relationships using agent-based modeling

Gunnar Dressler et al.

Correspondence to: Gunnar Dressler (gunnar.dressler@ufz.de)

Outline		**Guiding questions**	**Description**
I) Overview	I.i Purpose	I.i.a What is the purpose of the study?	The purpose of the model is to analyze the performance of disaster management and understand how it is affected by change (e.g. demographic, climatic, or technological). There are three main questions: (1) Which dimension of change has the most profound influence on the performance of disaster management? (2) Can we identify bottlenecks or critical thresholds for the capacities of disaster management to ensure protection? (3) How do these thresholds depend on the regional geographic and demographic setting?
		I.ii.b For whom is the model designed?	The model is designed for both scientists and stakeholders, as an exploratory tool to understand the functioning of disaster management under change and as a discussion tool to illustrate these results to experts, address possible shortcomings and highlight options for improvement.
	I.ii Entities, state variables, and scales	I.ii.a What kinds of entities are in the model?	- There is a single type of agents (DMOs), each representing a unit or group of helpers of a disaster management organization. - The physical environment of the model is characterized by a map that includes a transportation network (streets), rivers, flood prone areas and certain target sites as entities.
		I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterized?	DMOs: - team-size: number of helpers associated to the group - sandbags-capacity: transportation capacity, i.e. number of sandbags that can be transported by this group in one turn (corresponding to vehicle size) - moving-speed / speed-min / speed-limit: current moving speed as well as minimum and maximum speed of the DMO vehicle - assigned-task: one of ‘fill sandbags’, ‘transport sandbags’, ‘distribute sandbags’ - information-access: partial knowledge / full knowledge Disaster sites: - location: location of the site on the map and connection to the transportation network - sandbags-needed / sandbags-present / sandbags-distributed: respective number of sandbags needed in total to fulfil the task, currently present, and already distributed at the site - fixed?: true/false, indicating whether all tasks at the site are fulfilled or not Sandbag reserves: - location: location of the site on the map and connection to the transportation network - number-sandbags-filled: current number of sandbags filled and present at the site Transportation network: - street-type: one of ‘primary’, ‘secondary’, ‘tertiary’ or ‘motorway’ defining the type of the street - max-speed: speed limit, depending on street type Rivers and flood prone areas: - location: location on the map

		I.ii.c What are the exogenous factors / drivers of the model?	Different processes of change (e.g. demographic change, climate change) influence the system and thus the model dynamics. These effects are included via certain parameters that are systematically varied, such as the number of DMO agents N_{DMO} that can decrease as a consequence of demographic change.
		I.ii.d If applicable, how is space included in the model?	- The model is spatially explicit and uses GIS data as input for the location of rivers, flood prone areas as well as the transportation network.
		I.ii.e What are the temporal and spatial resolutions and extents of the model?	- Time: One time step (tick) represents one minute. There is no fixed time horizon as the model runs until all tasks are finished. - Space: The spatial extent corresponds to a defined region, e.g. a city, one grid cell has a resolution of 40 m x 40 m
	I.iii Process overview and scheduling	I.iii.a What entity does what, and in what order?	In each time step, the model checks first, whether all tasks are solved or not. If yes, the simulation stops, otherwise it steps into the main routine that is executed for each DMO agent: - At the beginning of the simulation each DMO gets assigned an initial task. In each subsequent time step, the model checks if the DMO has an assigned task, if yes, it carries out that task, otherwise a new task will be assigned. - Depending on the assigned task, the DMO agent will either: a) Fill sandbags, with a given rate, depending on the team-size of the DMO b) Transport sandbags, which involves loading sandbags onto the vehicle, moving along the transportation network, and unloading sandbags c) Distributing sandbags at the disaster site, with a given rate, depending on the team-size of the DMO - At specified intervals, DMO agents will also check whether they should switch to another task, e.g. if more capacity is needed to fill sandbags or to transport sandbags The main routine of the model is also depicted in the following figure:

import GIS Data (rivers, street network) setup disaster sites, DMOs
Initialization
End
yes
All tasks solved?
no
For all DMOs
no
Task assigned?
yes
yes
Sandbag supply sufficient?
no
Assign task
Distribute
Transport
Fill
Carry out assigned task
Check assignments (Task finished? Switching tasks?)

II) Design Concepts	II.i Theoretical and Empirical Background	II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to complexity and the purpose of the model?	- The model has been developed in order to depict the case of flood protection and disaster management in Saxony, however its generality should facility the transferability to other settings, too. - The model components are kept rather simple, as the model's purpose is to serve as a virtual lab, rather than as a prediction tool. - Complexity arises from the decision making of the agents and interaction between the agents and the model environment.
		II.i.b On what assumptions is/are the agents' decision model(s) based?	DMO decision making is based on simple heuristics, e.g. "if-then" rules.
		II.i.c Why is a/are certain decision model(s) chosen?	Under disaster conditions, DMOs rarely have the time to derive an optimal decision and have to rely rather on certain routines, past experiences or ad-hoc decisions. Therefore we employ simple "if-then" rules rather than more complicated optimization algorithms.
		II.i.d If the model / a submodel (e.g. the decision model) is based on empirical data, where does the data come from?	- The spatial setting of the model (rivers, flood prone areas, street network) is based on freely available GIS data. - Some decision making rules and their parameters are based on basic rules / guides used by disaster management organisations for flood protection.
		II.i.e At which level of aggregation were the data available?	- GIS data were available at a local (e.g. city) level.
	II.ii Individual Decision Making	II.ii.a What are the subjects and objects of decision-making? On which level of aggregation is decision-making modeled? Are multiple levels of decision making included?	- DMO units are the subject of decision making. - The object of decision making is the execution of tasks (filling, transporting, distributing sandbags) at certain target sites. - There is only one level of decision making.

		II.ii.b What is the basic rationality behind agents' decision-making in the model? Do agents pursue an explicit objective or have other success criteria?	- Agents follow certain heuristics when making decisions, based on the level of information available to them. - Their objective is to fulfil all tasks at all target sites in a preferably short amount of time.
		II.ii.c How do agents make their decisions?	See II.ii.b or III.iv.a for details.
		II.ii.d Do the agents adapt their behavior to changing endogenous and exogenous state variables? And if yes, how?	Yes. Agents can switch between tasks, when the need arises, e.g. when tasks at a specific disaster site are fulfilled, DMOs can switch to a different site or when sandbag supply at the filling site is running low, agents can switch from transporting/distributing sandbags to sandbag filling.
		II.ii.e Do social norms or cultural values play a role in the decision-making process?	No.
		II.ii.f Do spatial aspects play a role in the decision process?	Yes. The current location of the DMO agents and the distance to target sites is incorporated into their decision.
		II.ii.g Do temporal aspects play a role in the decision process?	DMO agents make decisions based only on the current state of the system.
		II.ii.h To which extent and how is uncertainty included in the agents' decision rules?	Uncertainty is not included in the decision making.
	II.iii Learning	II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?	No, learning is not included.
		II.iii.b Is collective learning implemented in the model?	No.
	II.iv Individual Sensing	II.iv.a What endogenous and exogenous state variables are	- DMO agents have full knowledge about the spatial settings of the model (transportation network, location of all target sites).

		individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?	- Each DMO agent has a certain level of information access about the state of each site: a) Full knowledge: complete knowledge about the state of all disaster sites at all times. b) Partial knowledge: knowledge can only be acquired through direct contact, i.e. when they are at a site, and will be remembered from then onwards. - The sensing is not erroneous.
		II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?	DMO agents are not able to sense the state variables of other agents.
		II.iv.c What is the spatial scale of sensing?	DMO agents have full spatial knowledge.
		II.iv.d Are the mechanisms by which agents obtain information modeled explicitly, or are individuals simply assumed to know these variables?	Agents are assumed to know the values of the sensed variables.
		II.iv.e Are costs for cognition and costs for gathering information inclu-ded in the model?	No.
	II.v Individual Prediction	II.v.a Which data uses the agent to predict future conditions?	Agents do not predict future conditions.
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?	Not applicable.
		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?	Not applicable.
	II.vi Interaction	II.vi.a Are interactions among agents and entities assumed as direct or indirect?	Interaction between DMO agents is indirect as they perceive the status of the target sites (disaster sites/sandbag reserve) and can adapt their behavior based on the actions of other agents at these sites.

		II.vi.b On what do the interactions depend?	Interaction does not depend on any parameters/conditions.
		II.vi.c If the interactions involve communication, how are such communications represented?	Not applicable.
		II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?	In the current model version, DMO agents act independently to solve their tasks. A coordination between of tasks between agents is planned.
	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect, and are affected by, the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?	Agents do not form collectives in the current model version.
		II.vii.b How are collectives represented?	Not applicable.
	II.viii Heterogeneity	II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?	Currently, within any single simulation all DMO agents are homogeneous in their properties.
		II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?	No.
	II.ix Stochasticity	II.ix.a What processes (including initialization) are modeled by assuming they are random or partly random?	- Disaster sites are randomly distributed at the beginning of each simulation. - The order in which DMO agents act in each time step is determined randomly by the Netlogo ‘ask’ command.

<table>
<tr><td rowspan="2"></td><td rowspan="2">II.x Observation</td><td>II.x.a What data are collected from the ABM for testing, understanding, and analyzing it, and how and when are they collected?</td><td>- For each simulation, the time needed to fulfil all tasks – the coping time – is measured as the main indicator of performance.
- When the model is run interactively (using the graphical interface), several variables can be monitored during a simulation run, e.g.
a) The current distribution of tasks onto the DMO agents
b) The degree to which tasks are fulfilled.
c) The location and movement of the agents, as well their movement speed.</td></tr>
<tr><td>II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)</td><td>As the agents act independently, we can observe if changes in their properties or their available resources lead to an increase or decrease in the resulting coping time at the end of the simulation.</td></tr>
<tr><td rowspan="6">III) Details</td><td rowspan="2">III.i Implementation Details</td><td>III.i.a How has the model been implemented?</td><td>The model has been implemented in NetLogo 5.2.0.</td></tr>
<tr><td>III.i.b Is the model accessible and if so where?</td><td>The model will be made accessible at openABM.org</td></tr>
<tr><td rowspan="3">III.ii Initialization</td><td>III.ii.a What is the initial state of the model world, i.e. at time t=0 of a simulation run?</td><td>At the beginning of the simulation, the spatial layout of the model is set up. A given number of disaster sites is distributed at random locations along rivers and flood prone areas. A given number of DMO agents is placed along certain fixed initial positions of the transportation network.</td></tr>
<tr><td>III.ii.b Is initialization always the same, or is it allowed to vary among simulations?</td><td>Initialization between simulations varies only in the location of disaster sites which is determined randomly and the location of DMO agents (which are fixed points on the transportation network, but the distribution of agents among these points can differ).</td></tr>
<tr><td>III.ii.c Are the initial values chosen arbitrarily or based on data?</td><td>Initial values are partly based on empirical data (e.g. spatial layout) and partly derived from sensitivity analysis that have been carried out with the model.</td></tr>
<tr><td>III.iii Input Data</td><td>III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time?</td><td>Yes, for the spatial layout of the model the following data was used:
<table>
<tr><td>Element</td><td>Data source</td><td>available at</td></tr>
<tr><td>Street Network</td><td rowspan="2">OpenStreetMap</td><td rowspan="2">http://download.geofabrik.de/europe/germany/sachsen.htm</td></tr>
<tr><td>Rivers</td></tr>
<tr><td>Flood prone areas</td><td>Saxonian State Office for Environment, Agriculture and Geology (Landesamt für Umwelt, Landwirtschaft und Geologie)</td><td>http://www.umwelt.sachsen.de/umwelt/wasser/8841.htm</td></tr>
</table>
Data has been preprocessed in ArcGIS for simplification.</td></tr>
</table>

	III.iv Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?	<u>setup:</u> - Imports all map data and sets up the world, i.e. creates DMO agents, disaster sites and sandbag-reserves and puts them on the map. - The spatial layout (i.e. rivers, floodprone areas and street network) is the same in every simulation. The location of sandbag reserve(s) can be fixed or determined randomly. The location of disaster sites and DMO agents will be determined randomly in each simulation, albeit with some constraints, e.g. disaster sites can only be placed within flood probe areas. <u>go:</u> - Main routine of the model that is carried out in each time step (*tick*). - Checks if there are still open tasks and loops through set of DMO agents and calls their tasks. <u>check-assignments:</u> - Carried out by each DMO agent when a) its current task is finished or b) b) after a specified amount of time (e.g. 30 min) to check whether it needs to switch to a different task. - Routine will check the current need for sandbag transportation / sandbag filling / sandbag distribution and if e.g. demand for sandbags at the sandbag reserve is higher than the current total filling rate, the DMO agent will switch to "fill sandbags" (if his previous task was "transport sandbags"). <u>fill-sandbags:</u> - Routine carried out by DMOs assigned to filling sandbags. If the DMO agent is not presently at a sandbag reserve, it will move to the nearest sandbag reserve. At a sandbag reserve, the agent will fill sandbags with a fixed rate (r-DMOs-filling) per tick that depends on the team-size of the agent. <u>distribute-sandbags:</u> - Routine carried out by DMOs at disaster sites when they are assigned to filling sandbags. The agent will distribute sandbags with a fixed rate (r-DMOs-distributing) per tick that depends on the team-size of the agent. <u>transport-sandbags:</u> - Routine carried out by DMOs assigned to transporting sandbags. - Consists of several subroutines that are carried out depending on the current location of the DMO agent, which can be either a sandbag-reserve, a disaster site, or some location on the street network.

			- Routine in pseudocode:

```
if (sandbags-loading?) {                          // loaded sandbags <
  if (at-sandbag-reserve?) {                      // transportation capacity
    load-sandbags
  }
  else {
    set sandbags-loading? = false
    move-to-sandbag-reserve
  }
}
else {                                            // enough sandbags loaded
  if (arrived at assigned disaster site?) {
    if (tasks at site finished?) {                // task has already been
      assign new disaster site*                   // finished, so a new target
      calculate-disaster-path                     // site will be assigned
      move-to-disaster
    }
    else {
      if (# sandbags loaded > 0) {
        unload-sandbags
      }
      else {
        set sandbags-loading? = true
      }
     }
    }
  else {
    move-to-disaster
  }
}

* assigned site depends on information access of the DMO agent (full / partial
knowledge)
```

<u>load-sandbags:</u>

- the agent loads sandbags at a sandbag reserve (with rate r-DMOs-loading) until the transportation capacity of the DMO agent is reached.

<u>unload-sandbags:</u>

- the agent unloads sandbags at a disaster site (with rate r-DMOs-unloading) until the number of loaded sandbags is zero.

move-to-disaster / move-to-sandbag-reserve:

- Subroutine that lets DMO agents move along the transportation network towards a given target site. Depends on a precalculated *path*, given by the calculate-[...]-path functions.
- Agents move forward on the transportation network towards the next node in their path. The distance that they move forward depends on their current moving-speed and the speed limit of the street. Once they reach the next node this node will be deleted from their path until they reach their final node = target site.
- DMO agents can accelerate and decelerate in the range of [speed-min, speed-limit] and the speed-limit of the street. They will accelerate to the maximum speed when the "road is free", i.e. when they don't encounter any other DMO agent in front of them and they move along the street. They have to decelerate at intersections (i.e. nodes in their path) and when they encounter other agents within a given distance in front of them.

calculate-disaster-path / calculate-sandbag-reserve-path:

- These routines are called to calculate that path through the transportation network to a) a specific target site or b) the nearest (i.e. shortest distance) target site. The path is calculated using the A*-search algorithm (Hart et al., 1968; Goldberg and Werneck, 2005; subroutine A*-path)

Plotting, output and some helper functions are not described here to maintain the conciseness of the description.

III.iv.b What are the model parameters, their dimensions and reference values?

Parameter	**Description**	**Standard value**
Global		
number-DMOs	number of DMO agents	20
number-disasters	number of disaster sites	40
number-sandbag-reserves	number of sandbag reserves	1
case-site	which case site	Leipzig / Neisse
DMOs specific		
DMOs-information-access	level of information access (partial knowledge / full knowledge, see II.iv.a)	partial knowledge
DMOs-sandbag-capacity	transportation capacity of DMO agent	500
r-DMO-filling*	rate for filling sandbags	0.6
r-DMO-loading*	rate for loading sandbags	1.5
r-DMO-unloading*	rate for unloading sandbags	1.5

r-DMO-distributing*	rate for distributing sandbags	1.3
team-size	number of helpers belonging to this DMO agent	10
speed-min / speed-limit	minimum and maximum moving speed of DMO agent	5 / 50 [km/h]
disasters specific		
sandbags-needed	number of sandbags needed at a specific site	depends on sandbags-needed-total and sandbags-needed-distribution
sandbags-needed-total	number of sandbags needed in total (across all sites)	50000
sandbags-needed-distribution	distribution of sandbag demand across sites (homogeneous: same demand at all sites, heterogeneous: different demand at each site)	homogeneous
sandbag-reserves specific		
initial-sandbags	number of filled sandbags already present at begin of simulation	0

* see Table in Supplement B for details

		III.iv.c How were submodels designed or chosen, and how were they parameterized and then tested?	The submodels were designed with the same "virtual lab" approach in mind as the whole model. The robustness of the submodels has been tested using global sensitivity analysis over an extensive parameter range to determine sensible sets of parameter combinations.

References

Goldberg, A. V. and Werneck, R. F. F.: Computing Point-to-Point Shortest Paths from External Memory., in SIAM Workshop on Algorithms Engineering and Experimentation (ALENEX 05), pp. 26–40., 2005.

Hart, P. E., Nilsson, N. J. and Raphael, B.: A formal basis for the heuristic determination of minimum cost paths, Syst. Sci. Cybern. IEEE Trans., 4(2), 100–107, 1968.

Model task	Assumption	Source	Model parameter
Sandbag filling	Filling rate for sandbags: - Average: 40-60 sandbags per helper per hour - Trained helpers: 80 sandbags per helper per hour	[1] *Taschenkarte Deichverteidigung*, THW Ortsverband Emden, as of 12/2007, obtainable from www.deichverteidigung.de	$r_{filling}$ = [0.6,1.2] S x H x min^{-1} = [36,72] S x H x h^{-1} S – Sandbags H – Helper
	Filling via funnel and tying sandbags: - 180 sandbags per hour in a group of 5-6 helpers ≈ 30-36 sandbags per hour per helper	[2] *Umgang mit Sandsäcken und deren Verwendung*, Udo Wawerek THW Ortsverband Dinslaken	
Sandbag loading / unloading	Loading / unloading from truck (by hand): - If distance to truck < 10 m: 80 sandbags per helper per hour	[2]	$r_{loading}$ / $r_{unloading}$ = [1.0,2.0] S x H x min^{-1} = [60,120] S x H x h^{-1}
	Loading / unloading (palettes): - If filled sandbags are directly stored on palettes (~ 50-70 Sandbags per palette), they can be loaded much faster	[1], *estimated value*	
Sandbag distribution	Distribution at target site (i.e. dike): - 80 sandbags per helper per hour	[1]	$r_{distributing}$ = [1.0,1.3] S x H x min^{-1} = [60, 78] S x H x h^{-1}
Transportation	Transportation capacities: - calculated from average sandbag weight of 15-20 kg [1] (see table A)	Various technical specifications: - [3] *THW Hamburg Nord* http://www.thw-hamburg-nord.de/kfz/fgr-hang1.htm - [4] *PrimoCargo* http://www.primocargo.de/deutsch/medien/info-pool/lkw-auflieger - [5] *Der Unimog 300/U400/U500. Technik. Fakten. Daten.* DaimlerChrysler AG, http://www.mercedes-benz.com/unimog	$DMO_{Capacity} \in$ {250, 500, 1000, 2000} sandbags per DMO unit
	Vehicle speed / speed limits: (see table B)	[6] *Straßenverkehrs-Ordnung (StVO): § 3 Geschwindigkeit, § 18 Autobahnen und Kraftfahrstraßen*, http://www.gesetze-im-internet.de/bundesrecht/stvo_2013/gesamt.pdf	Speed limits per street type (see table C)

Type	Loading capacity: Weight [t]	Loading capacity: Sandbags
Transporter	1 – 2	50 – 120
Small truck (e.g. „Unimog")	3 – 7	200 – 400
Large truck	10 – 15	500 – 1000
Lowloader	20 – 40	1000 – 2500

Type	Motorway	Outside built-up areas	Inside built-up areas
Car / transporter [< 3.5 t]	130 km/h[1]	100 km/h	50 km/h
Truck [3.5 – 7.5 t]	80 km/h	80 km/h	50 km/h
Truck / lowloader [> 7.5 t]	80 km/h	60 km/h	50 km/h

[1] recommend maximum speed

Type	Speed limit
motorway	80 km/h
	60 km/h
primary	50 km/h
secondary	50 km/h
tertiary[2]	30 km/h

[2] assumed as residential areas with 30 km/h zones