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SIMULATION OF CONTAINER DISCHARGE DYNAMICS USING MODIFIED CELLULAR AUTOMATA

PÉTER VERES[1]

Abstract: *In the field of physical logistics, efficient and precise control of material flow during the emptying of containers such as silos and wagons is crucial. This study introduces a not conventional cellular automaton model to simulate spillage from containers. The model is implemented using Excel macros, providing a user-friendly and accessible platform for logistics professionals. By modifying the traditional cellular automaton framework, the simulation can accurately represents the dynamics of material flow during container emptying processes. The proposed method allows for fine-tuned control over the spillage by integrating specific constraints and parameters, enhancing operational efficiency and reducing material loss. The versatility of the model makes it applicable to a wide range of logistical scenarios, demonstrating its potential as a valuable tool in physical logistics management.*

Keywords: *cellular automaton, container emptying simulation, silo physics, excel macro*

1. INTRODUCTION OF CELLULAR AUTOMATA IN THE FIELD OF LOGISTICS

Cellular automata (CA) are discrete, abstract computational systems that have been extensively studied for their ability to model complex systems through simple, local interactions. Initially introduced by John von Neumann and Stanislaw Ulam in the 1940s, CAs consist of a grid of cells, each of which can be in one of a finite number of states. [1] The state of each cell in the grid evolves through discrete time steps according to a set of rules based on the states of neighbouring cells. This simplicity in design yet complexity in behaviour has made cellular automata a powerful tool for simulating a wide range of natural and artificial systems [2].

In logistics, the utility of cellular automata extends beyond theoretical fascination to practical applications, particularly in the modelling and simulation of physical logistics processes. These processes often involve the movement, storage, and handling of goods, all of which can be effectively represented using CA models. By leveraging the computational simplicity and flexibility of cellular automata, researchers and practitioners can gain insights into the dynamics of logistics systems, optimize operations, and develop more efficient strategies for resource management [3].

One prominent application of cellular automata in logistics is the simulation of material flow and distribution in warehouses, silos, and transportation networks. For example, in a silo or container, the process of filling and emptying can be modelled as a series of local interactions between particles, which are analogous to the cells in a CA grid. By modifying the rules governing these interactions, it is possible to simulate various scenarios, such as the effect of different container shapes, flow rates, and particle properties on the overall behaviour of the system. These claims and this study were inspired by Professor Andre Katterfeld’s work [4].

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[1] Senior lecturer, University of Miskolc, Miskolc, Hungary
peter.veres@uni-miskolc.hu

Additionally, cellular automata can be used to model and optimize the layout and operation of warehouses. The movement of goods within a warehouse can be represented by CA models where cells represent storage locations and states represent the presence or absence of items. Rules can be designed to mimic the behaviour of workers picking and placing items, allowing for the simulation of different strategies for order picking, replenishment, and inventory management. Such models can help identify bottlenecks, optimize storage policies, and improve the overall efficiency of warehouse operations [5].

The use of CA in logistics is not limited to static environments. Dynamic systems, such as traffic flow and transportation networks, can also be effectively modelled using cellular automata. For instance, the movement of vehicles on a road network can be simulated using a CA model where cells represent road segments and states represent the presence or absence of vehicles [6]. The rules governing the state transitions can incorporate various factors such as traffic signals, speed limits, and driver behaviours. These models can help in understanding traffic patterns, evaluating the impact of infrastructure changes, and developing strategies for traffic management and control [7].

Moreover, the adaptability of cellular automata makes them suitable for integrating with other computational techniques. For example, combining CA with machine learning algorithms can enhance the predictive capabilities of logistics models. Machine learning can be used to identify patterns and optimize rules in CA models based on historical data, leading to more accurate and robust simulations. This integration can be particularly useful in complex logistics systems where traditional modelling approaches may fall short [8].

The goal of this research is to provide a new ground for cellular automata simulations in logistics, where it can be shown that, it’s a versatile and powerful framework for modelling and simulating. In the main part of the research a 2D spillage simulation will be shown, with multiple starting phases which use CA as a decision-making device.

2. MODEL OF SPILLAGE SIMULATION

In this study, a spillage model was developed using Excel VBA, leveraging the accessibility and ease of use of the tool. The model is based on cellular automata behaviour, which has been adapted to suit the specific needs of the spillage process. While the behaviour in this model resembles traditional CA, it diverges from the original concept in significant ways. Unlike classical CA rules, where cells change state based solely on their neighbours (like J Conway’s Game of Life [9]), this model allows cells to change other cells. This variation enables the system to operate more efficiently and produces a more visually dynamic output. The inclusion of distant cell interactions was necessary to accelerate the simulation process, especially when dealing with large datasets. Each step of the iteration evaluates the state of a cell and its neighbours, following a set of predefined rules. The first rule that is satisfied will be applied immediately, preventing further rule evaluations. This ensures that only one change is made per iteration, maintaining computational efficiency.

As figure 1. states there were 6+1 rules declared, where should a material unit go:

0. if this is a non-movable grid skip to next
1. if there are an empty space 2 grid-spaces downward
2. if there are an empty space 1 grid-spaces downward
3. if the lower right diagonal space is empty
4. if the lower left diagonal space is empty
5. if the 1 down and 2 right grid space is empty

6. if the 1 down and 2 right grid space is empty

If none of these are true, then skip to the next grid cell.

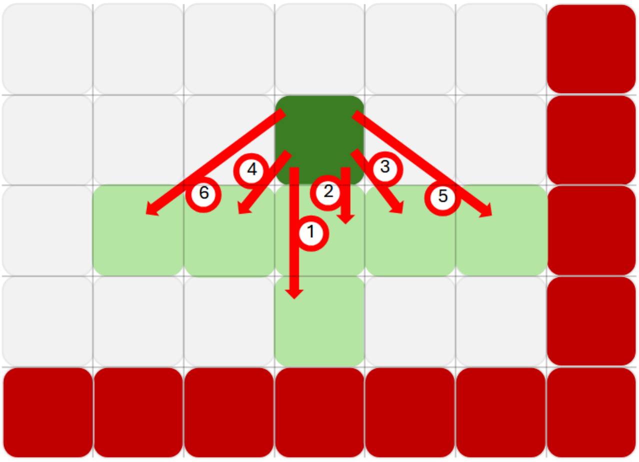

Figure 1. *Rules for material displacement*

These rules are only examples, nothing is set in stone. The rules can be used to control the speed of the discharge (e.g. the more the material go downward, the sooner the container empties, like rules 1 and 2) or to set the natural or moving splay of the material, which in this grid format. If the grid represents a square unit, the 45° splay can be achieved by a downward and a lateral movement. This is represented by rule 3 and 4. Rule 5 and 6 represents a 26.57° splay, since the ratio of downward/lateral motion is 1:2. This can be changed easily and almost any rational number of angles can be specified, if a sufficiently small grid size is specified. For example, an angle of about 35°, which is tan35°=0.7002, can be set simply with a 7:10 downward/lateral movement. The only problem with too big numbers of the denominator and numerator is computational power. If we cut the grid into smaller and smaller pieces, the computer has to individually check each cell for every iteration, where the computational power can increase in 2D $O(n^2)$ and in 3D $O(n^3)$, with additional rules to check.

3. SIMULATION OF DISCHARGE FROM DIFFERENT CONTAINERS

Based on the previously described rules, a simulation tool was developed within an Excel spreadsheet to visually model spillage dynamics in various container configurations. The current implementation updates the spreadsheet after each individual cell's state change, resulting in a relatively slow performance. On typical machines, the model can process between 100 and 1,000 cells per second.

To improve performance, a less visually detailed approach could be implemented. For instance, instead of updating the table after every cell modification, the entire grid could be refreshed after a full iteration is completed. Alternatively, for simulations involving larger datasets, the grid could be divided into iteration packages, allowing millions of cells to be updated per second or even more with an optimised with a program made specifically for this in another programming language. However, these optimizations would reduce the visual feedback provided during the simulation, prioritizing computational efficiency over real-time visualization. For colouring conditional formatting was used. This again a highly computational hungry function at this level.

The conditions were:

- -1, colour red: represents the non-movable objects (walls, blockages)
- 0, no colour: represents, the empty grid cells and the openings in the walls
- 1&2, green colours: represents, the movable materials (fluids and bulk materials, like grains)

There is no distinction between material 1 & 2, only representation of layers for visual aid.

As shown in Fig. 2, when no obstacles are present, the emptying process proceeds smoothly in a regular container. However, with a 1:2 splay, some residual material remains in the wider container, reflecting the complexity of spillage dynamics. The rules governing the model ensure that the first condition to be met is applied immediately, streamlining the execution process. These rules are carefully structured to mimic real-world spillage scenarios, allowing the model to predict outcomes accurately. The iteration process considers the current state of a cell and its neighbours, triggering changes according to a predefined set of rules. The altered behaviour accelerates the simulation and provides more detailed visual feedback.

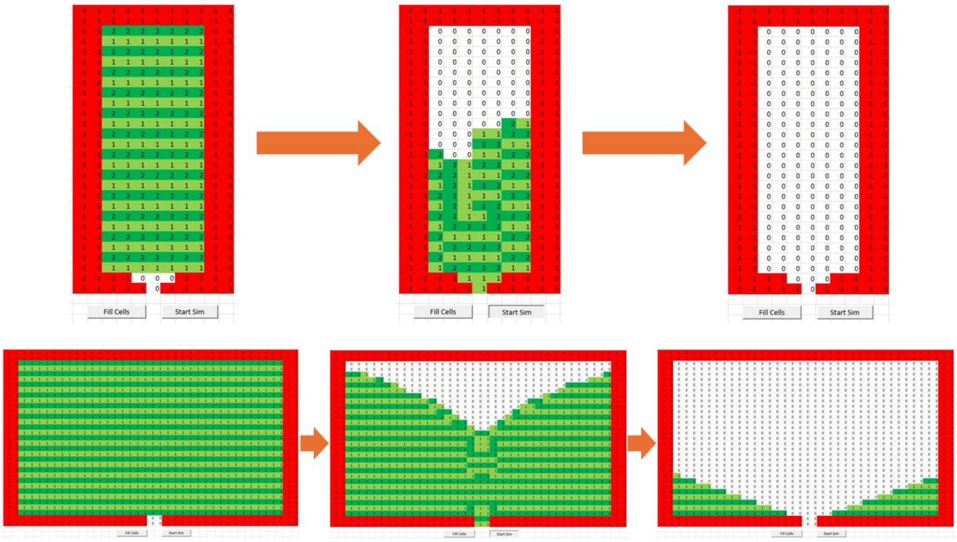

Figure 2. *Regular container drainage*

In Fig. 3, various types of drainage nozzles are shown, each of which can be simulated to observe their effects on discharge speed. The model is capable of accurately representing how different nozzle shapes influence the rate of material flow, capturing subtle variations in discharge performance. Additionally, the simulation can easily handle irregular shapes, allowing for the exploration of complex geometries without sacrificing accuracy.

This flexibility makes the model well-suited for simulating real-world conditions where non-standard nozzle designs are often encountered. By adjusting nozzle types within the simulation, users can evaluate how changes in design impact the overall efficiency of the discharge process. This adaptability enhances the model's practical utility, making it a valuable tool for engineers and researchers interested in optimizing bulk/fluid dynamics in different systems.

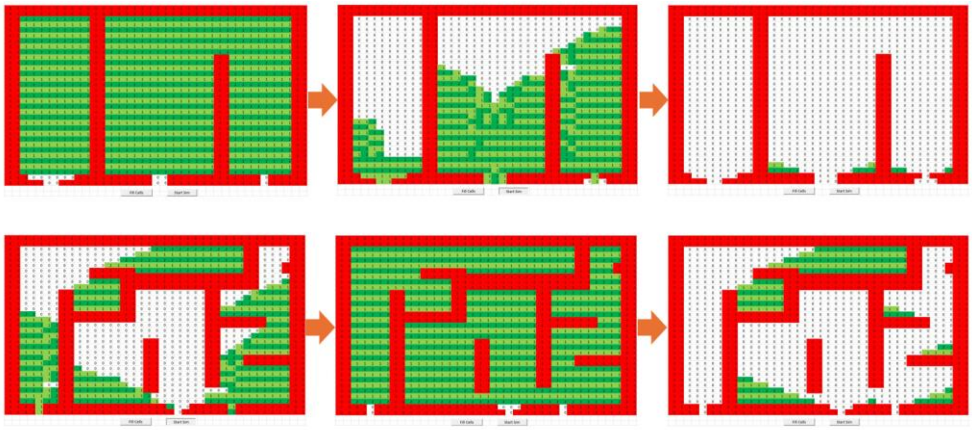

Figure 3. *Irregular container drainage*

4. CONCLUSIONS

In conclusion, cellular automata can provide a robust and flexible framework for simulating complex systems, including logistics and fluid dynamics. By applying simple local rules, CA can model a wide range of behaviours, making them particularly useful for applications like spillage simulation, as demonstrated in this study. The discharge model developed using Excel VBA effectively illustrates the potential of CA to handle both regular and irregular geometries, as well as various drainage mechanisms.

This modelling can be effectively used in various industries to simulate the behaviour of discharge containers, especially for granular materials, powders, or fluids. In the mining and bulk material handling industry, it can helps predict material flow and blockages in silos and hoppers, optimizing discharge processes for materials like ores and cement. In pharmaceutical manufacturing, CA can be applied to simulate the discharge of fine powders and granules during drug production, ensuring smooth flow and preventing clogging in granulation equipment. The food and beverage industry benefits from CA by improving the flow of grains, powders, or liquids from storage containers, enhancing production efficiency for products like flour or sugar. In the chemical industry, simulations assist in handling granular or liquid chemicals, optimizing discharge from storage tanks and reaction vessels in large chemical plants. Waste management and recycling operations use CA to model the discharge of waste materials from containers, enhancing sorting and processing efficiency. In agriculture, CA aids in the flow of grains and seeds from silos, optimizing discharge for packaging or planting operations. Construction material production also benefits from CA simulation by improving the handling of cement, sand, and aggregates, ensuring smooth flow and reducing blockages in silos and mixers.

Although the current implementation faces limitations in computational speed due to real-time cell-by-cell updates, optimizations such as batch processing and iteration packages could significantly improve performance. These trade-offs between visualization detail and computational efficiency highlight the flexibility of CA-based models. Furthermore, the ability to adapt rules and grid resolution allows for precise control over simulation parameters, making the model suitable for a wide range of real-world applications in logistics, container drainage, and material flow analysis.

Overall, this study underscores the potential of integrating CA models into practical logistics scenarios, providing valuable insights into spillage behaviour, discharge processes, and system optimization. Future work could explore further computational optimizations and extensions to 3D simulations to enhance the model's applicability to larger and more complex logistics systems.

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