SYSC 4906 G – Modeling and Simulation

Cell-DEVS Simulation for Segregation Modeling

By Arthur Atangana – 101005197

Submitted to: Professor Gabriel A. Wainer

Department of System and Computer Engineering

Faculty of Engineering

Carleton University

April 26th, 2025

Table of Contents

1. Introduction

Complex social patterns often emerge based on hard to define parameters and factors. One particular example of these patterns being generated in day-to-day observable phenomena is the idea of residential segregation: How cities or neighborhoods often end up divided based on racial, cultural or socioeconomic divides. These patterns can often be, at first glance, attributed to urban planning or intentional, codified discrimination but can emerge because of simple, decentralized decisions made by individuals based on their unique sets of personal preferences. Segregation modeling explores these ideas where small-scale interactions generate large scale geographic structures and patterns.

The first models demonstrating how individual preferences, even those of relatively tolerant people, would lead to unintended and widespread segregation came about in 1970 by economist Thomas Schelling. Schelling's model of segregation[1] applies very well to cell-DEVS as it is based on the internal behavior of each individual agent, which can be translated into cell behavior and extended with other factors. Schelling's model demonstrated that even mild preferences would lead to a highly segregated society.

1.1. Motivation

Modeling segregation using Cell-DEVS is motivated by the desire to get better insights on how localized interactions among individuals give rise to broader social patterns, specifically residential segregation. This approach enables researchers to explore various scenarios, experiment with different parameters, and uncover emergent patterns that may otherwise remain hidden. Through Cell-DEVS-based segregation modeling, the aim is to better understand the underlying mechanisms of segregation, inform urban planning and policymaking, and potentially devise strategies to promote more integrated, resilient, and inclusive communities.

1.2. Goals

The primary goal of modeling segregation using Cell-DEVS is to simulate and analyze how individual behaviors and neighborhood preferences contribute to the formation of segregated spatial patterns over time. By modeling two opposing groups, we look at how they move in space based on different factors like their proclivity to live near others like or unlike them, the effect of obstacles like a highway or other terrain the separates space, and economic factors like the quality of the residence and its impact on the individual's decision-making.

1.3. Contributions

This approach was done by modeling the population in Asymmetric Cell-DEVS, which proved very useful to design obstacles like walls and custom geometry. While for simplicity in the examples, a 10x10 grid was used, modeling in the obstacle proved insightful to analyze the movement patterns that emerged. The model was implemented in cadmiumV2 and is available at https://github.com/ArthurAtangana/segregation-simulation

2. Background

Segregation has been a social issue in the United States since its inception. The reasons that have contributed to it are often institutional, codified into law and practices like housing discrimination, loan discrimination, education, healthcare, employment and transportation. While these specific examples have been the target of civil right protests and have been mostly done away with, America is still a segregated country in many ways. While written segregation practices don't really exist anymore, social customs and individual preferences end up paving the way for the current segregation in urban cities in most states. The first models of residential segregation meant to look at these non-obvious causes that end up creating segregated neighborhoods: those individual choices stemming from bigotry, are not something that can be demonstrated in concrete laws or policies. Thomas Schelling's Agent based model explores this idea that those behaviours, even if unintentional or small, end up in creating strong racial divides within a neighbourhood.

Cell-DEVS (Cellular Discrete Event System Specification) is a formal modeling paradigm that extends classical cellular automata by integrating the DEVS (Discrete Event System Specification) framework[2]. While traditional cellular automata rely on synchronous updates and simple rule sets, Cell-DEVS introduces asynchronous and event-driven behavior, allowing each cell to evolve based on local rules and external inputs with individual delays. This makes it particularly well-suited for modeling complex, time-sensitive phenomena in spatially distributed systems.

In Cell-DEVS, a model consists of a grid of interconnected cells, each governed by a local transition function. These cells interact with their neighbors based on a defined topology (e.g., Moore or Von Neumann neighborhoods), and the asynchronous nature of the model allows for more realistic timing and responsiveness. Because Cell-DEVS decouples timing from state transitions, it enables finer control over how different components of a system evolve over time.

Asymmetric Cell-DEVS is a more recent extension designed to address limitations in uniform neighborhood structures. In traditional Cell-DEVS, all cells typically follow the same neighborhood and transition rules. Asymmetric Cell-DEVS allows each cell to have its own neighborhood structure and customized transition logic, enabling heterogeneous spatial interactions. This is especially useful for modeling systems where interactions vary based on position, context, or agent-specific factors.

Segregation dynamics involve spatial interactions, local decisions, and asynchronous movement, which is exactly the kinds of behaviors that Cell-DEVS and Asymmetric Cell-DEVS are built to capture. With Cell-DEVS, we can simulate how individuals respond to their immediate environment over time, incorporating delays and thresholds that reflect real-world decision-making processes. Asymmetric Cell-DEVS enhances this by allowing each agent (or cell) to have a unique set of neighbors or rules, representing diverse social preferences, constraints, or environmental factors.

This flexibility makes the modeling more realistic and expressive, especially for complex urban or social settings where uniform assumptions do not hold. By using Cell-DEVS, we gain both the formal rigor of DEVS-based modeling and the spatial expressiveness of cellular systems. This is what makes it an ideal tool for studying segregation phenomena and testing the impacts of various intervention strategies.

3. Model Definition

3.1. Grid Based Cell-DEVS Model

This project approached modeling in two steps. The first initial model was a Cell-DEVS Model consisting of two groups A and B represented by 1 and -1 respectively. Simply put, it defines the basic behaviour of a cell as a simple test of its neighbours being like it: Using a 3 by 3 Moore neighborhood (figure 1), the cell looks at its neighbours with the following sets of rules:

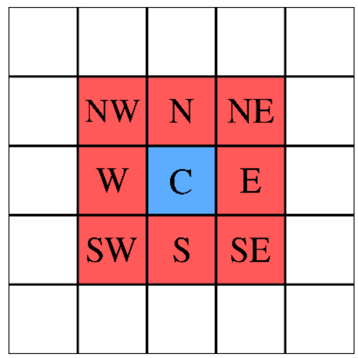


Figure 1: *3 by 3 Moore neighborhood*[3]

3.1.1. Rules

- For every cell with a value of 1, calculate the sum of its 3x3 Moore neighborhood (excluding the center cell):
    - If the sum < -0.5, the cell value moves to the first available empty cell and sets its state to empty.
    - Else: the cell remains in its current state.
- For every cell with a value of -1 calculate the sum of its 3x3 Moore neighborhood (excluding the center cell):
    - If the sum > 0.5, the cell value moves to the first available empty cell and sets its state to empty.
    - Else: the cell remains in its current state.

3.1.2. States:

Value	Description
0	Empty Cell
1	Group A
-1	Group B

3.1.3. Cell-DEVS formal specification

- X = Ø
- Y = Ø
- S = {0, 1, −1}
- delay = inertial
- N = Moore's 3x3
- d = 1
- τ =

```
// Count the number of different-type neighbors
for (const auto& [neighborId, neighborData] : neighborhood) {
    double neighborValue = neighborData.state->value;

    if (neighborValue != 0.0) { // Ignore empty cells
        totalNeighbors++;
        if ((state.value > 0 && neighborValue < 0) || (state.value < 0 && neighbor
            differentNeighbors++;
        }
    }
}

// Move if more than 50% of non-empty neighbors are different
if (totalNeighbors > 0 && (double)differentNeighbors / totalNeighbors > 0.5) {
    if (state.value == 1.0){
        numA++;
    }
    else if (state.value == -1.0) {
        numB++;
    }
    state.value = 0.0; // The current position becomes empty
}

return state;
```

- D = 1
- δint = Cell-DEVS specification
- δext = Cell-DEVS specification
- λ = Cell-DEVS specification

3.2. Asymmetric Cell-DEVS model

A more complex and interesting application of rules and states for segregation uses an Asymmetric Cell-DEVS model to allow for more complex states of cells and include more variables in the model. The core of the project resolves around the idea that there are many individual preferences that factor in the decision to stay, which might increase or counteract the desire for a relatively tolerant or intolerant person to segregate themselves away from a specific group. The Asymmetric Cell-DEVS model allows for the following modeling characteristics:

- Configuration of cells to have variable ratios of tolerance. In one experiment, the groups might want to be surrounded by at least 50% similar cells, while in another, this ratio might drop to 10%. This would, according to Schelling's segregation model, still result in segregation, but the asymmetric model will allow for observation on the strength of that model.
- Another addition is the idea that residents need to stay in a location for longer periods of time. Realistically, a resident cannot be expected to move instantly if they locate to an undesirable neighborhood. Adding a minimum stay period for a cell adds the dynamic that a resident will slowly see its neighborhood transform into a desirable or undesirable one, thus affecting their decision to relocate.
- Since humans need social interactions, if a resident is surrounded by empty cells, it will move as soon as possible. This prevents patterns of individual segregation to appear.
- Another common occurrence of segregation in cities, is the stark segregation along landmarks, natural geographic features like rivers or even manmade separation with walls and highways (see figure 2) Asymmetric DEVS allows for this inclusion in the model by allowing for custom neighborhood definitions. A cell could be made to look at all the cells surrounding it, aside from the ones on its left for example.

Figure 2: *Segregation Based on Geographic or Manmade Obstacles.*[4]

- Lastly, the quality of the location is often a high indicator of a resident's desire to stay and will likely offset some amount of intolerance to a different group. Adding states for specific cells to be desirable or not also plays into the desire of a resident to move. Such examples could be that the building itself is nice, the schooling system in the location is great, or a combination of many factors.

3.2.1. Rules

- A cell is either a valuable location (v) or not (null)
- A cell can be empty, 1 or -1.
- A resident must stay for at least 5 time-units in the cell. After which it is allowed to decide on its movement.
- If a resident is surrounded by empty cells, it moves.
- If cell.value = 1:
    - $C_{i+1}.value + C_{i+2}.value + C_{i+3}.value + C_{...}.value + C_n.value$ where the computed sum is the sum of the values of the neighborhood cells of C_i who's values are equal to C_i.
        - If $C_i.isValuableLocation = true$, add 1 to the count of similar neighbors. This acts as a +1 weight on the value of the land the individual cell is currently on.
    - Compute the difference between the total of similar neighbors (including the valuable location if evaluated to true) and the total amount of neighbouring cell that have a resident on it (exclusion of empty cells).
        - If smaller than the set ratio for the experiment, the cell needs to move.
        - Else, the cell stays.
- If cell.value = -1:
    - $C_{i+1}.value + C_{i+2}.value + C_{i+3}.value + C_{...}.value + C_n.value$ where the computed sum is the sum of the values of the neighborhood cells of C_i who's values are equal to C_i.
        - If $C_i.isValuableLocation = true$, add 1 to the count of similar neighbors. This acts as a +1 weight on the value of the land the individual cell is currently on.
    - Compute the difference between the total of similar neighbors (including the valuable location if evaluated to true) and the total amount of neighbouring cell that have a resident on it (exclusion of empty cells).
        - If smaller than the set ratio for the experiment, the cell needs to move.
        - Else, the cell stays.
- If cell.value = 0:
    - Do nothing.

3.2.2. States

Value	Meaning
0	Empty location
0v	Valuable location, empty
1	Group A
1v	Group A, valuable location
-1	Group B
-1v	Group B, valuable location

3.2.3. Asymmetric Cell-DEVS formal specification

- $X = \{1, -1\}$
- $Y = \emptyset$
- $C = \{c1, c2, c3, \dots, c100\}$
- $IC = \{c_i \in C\}$ see 3.2.3.1
- $EIC = \emptyset$
- $EOC = \emptyset$

3.2.3.1. Cell specifications

- $X_i^N = \{1, -1\}$
- $X_i^E = \emptyset$
- $Y_i = \{1, -1\}$
- $S_i = \{0, 0v, 1, 1v, -1, -1v\}$
- delay = inertial
- N = Moore Neighborhood. Example: $N_{c5} = \{c4, c6, c14, c15, c16\}$
    - Some cells could have a wall on the left side for example: $N_{c5} = \{c4, c14, c15\}$
- d = 1
- τ =

```
// trying out a cell for at least 5 time units before looking to move
        state.timePassed++;
        if (state.timePassed < 5) {
                return state;
        }
    // assign value if there is one to be assigned, and add cellID:0 pair if not already in the map
        if (state.value == 0.0) {
                state.value = cellsAssignment[cellID]; // assign value
                cellsAssignment[cellID] = 0.0; //reset cell assignment tracker
                if (state.value != 0){
                        state.timePassed = 0; // restart the counter for the cell
                }
                return state;
        }
        // check if cell needs to move
        if (cellNeedsToMove(state, neighborhood)){
                moveCell(state);
                // reset state of the cell
                state.value = 0.0;
                return state;
        } else {
                return state;
        }
```

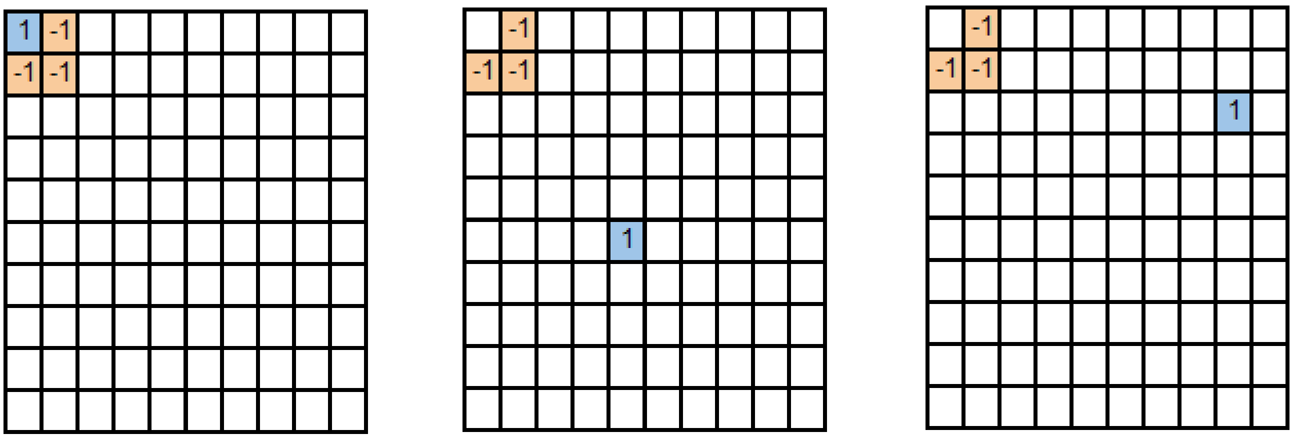
- D = 1
- δint = Cell-DEVS specification
- δext = Cell-DEVS specification
- λ = Cell-DEVS specification

4. Simulation Results

4.1. Experiment 1

The most basic configuration highlighting a single cell belonging to group blue (1) around 3 group yellow (-1) cells with a 50% ratio. (figure 3)

Based on the basic rules, the blue cell must move as it is a strong minority. After 5 time-units, the cell moves to a random location. Since the majority of the grid is empty, the cell will have to move forever as there are no suitable locations for it to stay long term.

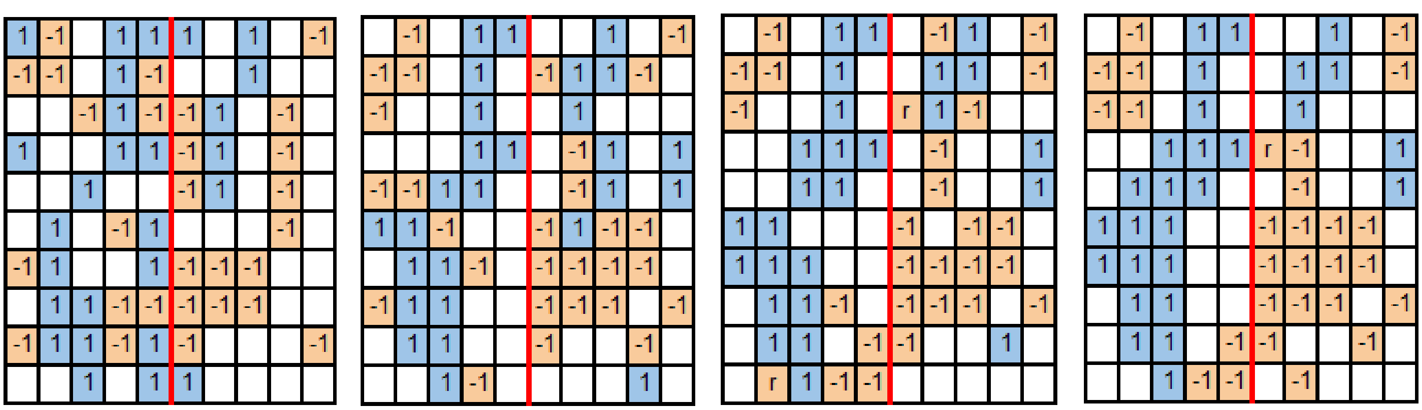


Initial state (t=0) *Intermediate state (t=10)* *Final state (t=499)*

Figure 3: *Experiment 1 – Single cell infinite movement*

4.2. Experiment 2

Experiment 2 introduces a more complex system using asymmetric DEVS. An obstacle is placed in the middle of the map (red line in figure 4). The cells immediately to the right of the red line cannot see the cells immediately to the left of it and vice versa. This result in strong segregation with the groups being mostly segregated on each side of the map instead of smaller evenly distributed groups.

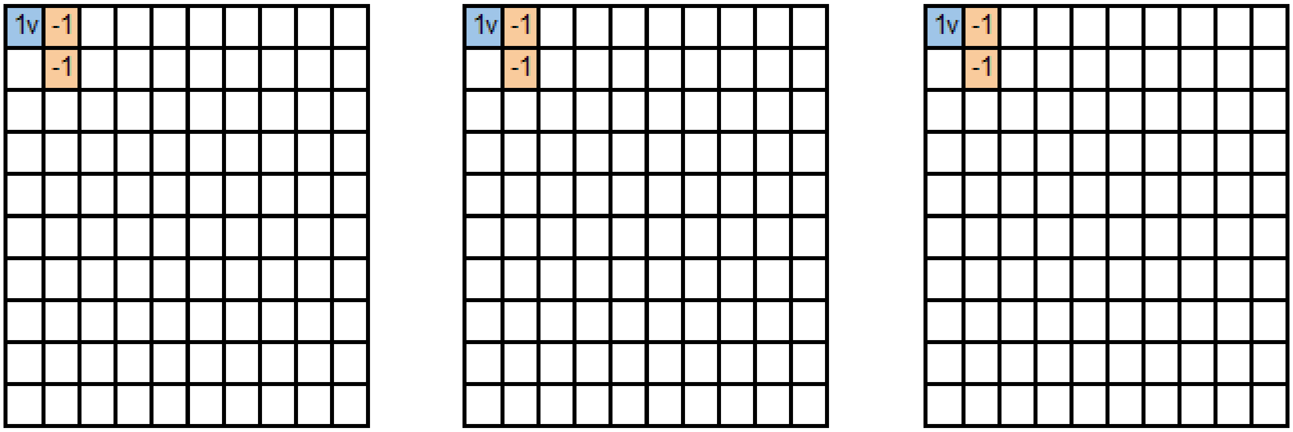


Initial state (t=0) *Intermediate state (t=7)* *Intermediate state (t=14)* *Final state (t=499)*

Figure 4: *Experiment 2 – Obstacle geography*

4.3. Experiment 3

Experiment 3 introduces valuable location on the map. The simplest case is one where blue is in a valuable location at a ratio of 50%, adding weight to its decision to move. Normally, blue should want to move as it is under-represented. Because of the added value of the location however, blue will stay there until the spot bellow it is changed to yellow. As can be seen in figure 5, the yellow cells also do not move as they are both in higher proportions in their respective neighborhoods.

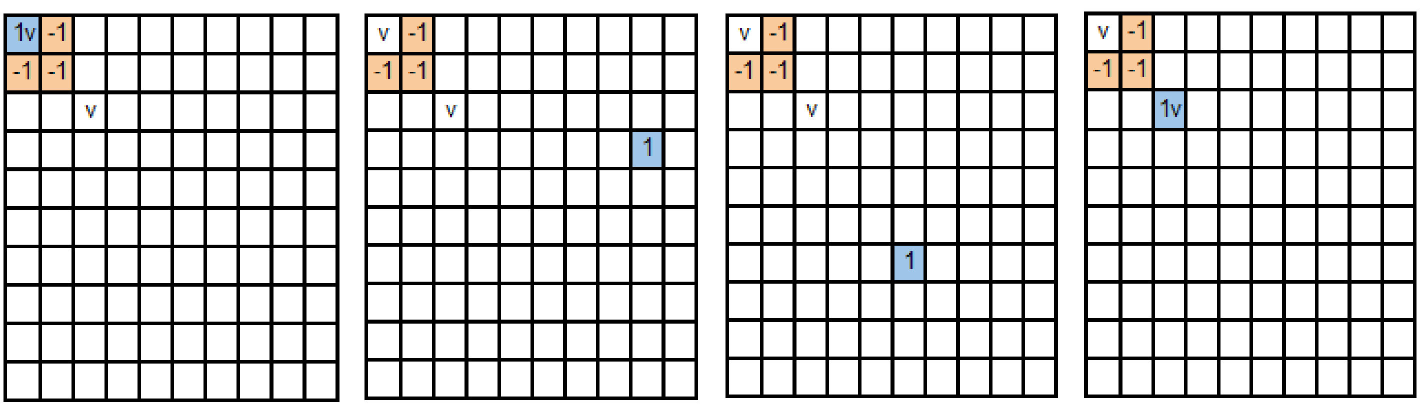


Initial state (t=0) *Intermediate state (t=10)* *Final state (t=499)*

Figure 5: *Experiment 3 – Remaining in Valuable Location*

4.4. Experiment 4

Experiment 4 demonstrates the logic of valuable locations. Similarly, to experiment 3, the single blue cell is initially in a valuable location c1. However, because the representation of yellow cells is past the 50% threshold, the cell now wants to move. It will move around the map at random. The added valuable cell at position c23 remains empty until blue randomly moves there. When looking at its default 3x3 Moore neighborhood, the blue cell is now satisfied as there is only 1 yellow cell and its current location is a valuable one.



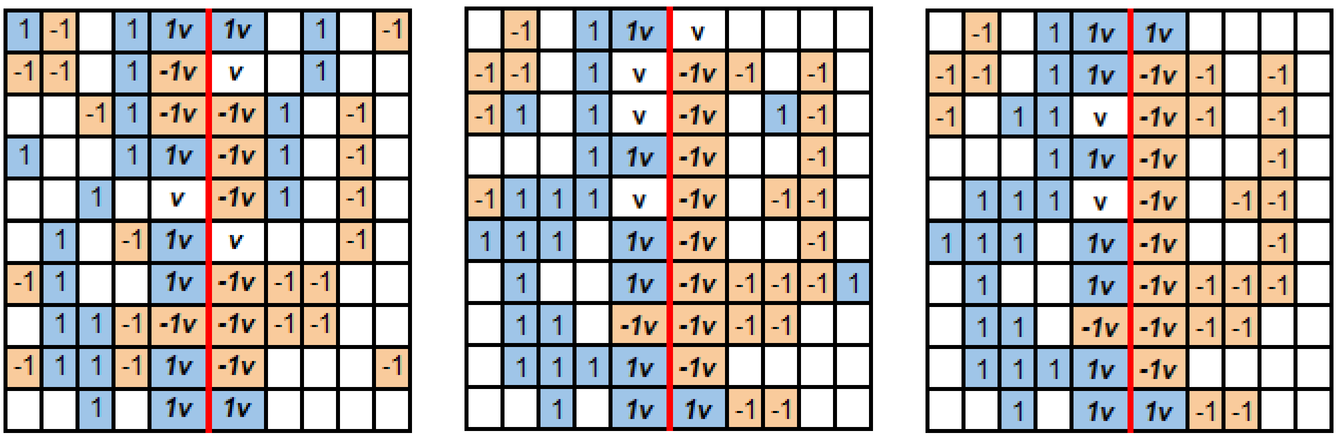
Initial state (t=0) *Intermediate state (t=7)* *Intermediate state (t=14)* *Final state (t=499)*

Figure 6: *Experiment 4 – Moving out of Valuable Location*

4.5. Experiment 5

Experiment 5 combines all the previous experiments into one where we can observe a couple of findings:

The wall in the middle of the map (figure 7) is surrounded by valuable locations. As time progress, we see similarly to experiment 2 a strong segregation of colors on their respective side of the map, but this time with a much higher concentration around the wall where the valuable locations are.



Initial state (t=0) *Intermediate state (t=10)* *Final state (t=499)*

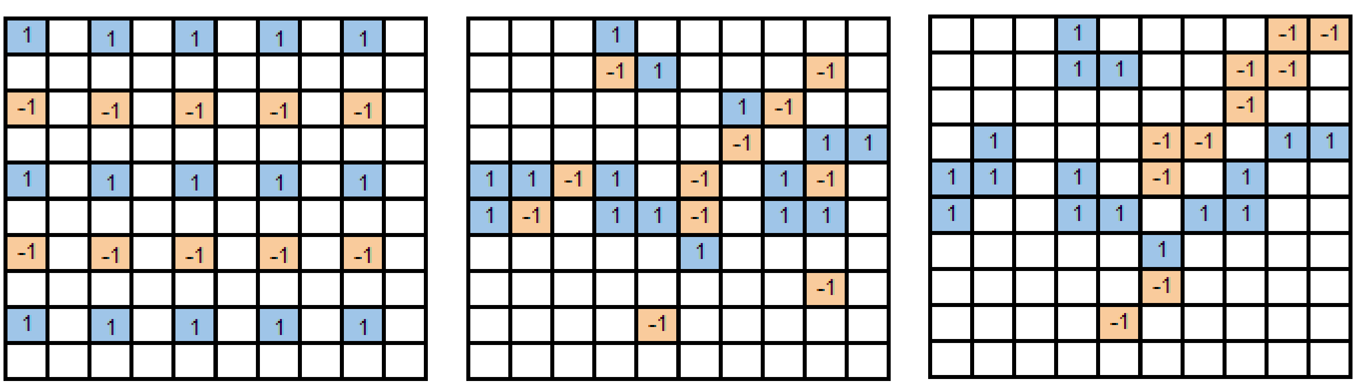
Figure 7: *Experiment 5 – Combined experiment*

4.6. 50% ratio Experiment

While some highlight that Thomas Schelling's findings that even those scenarios where groups are tolerant of one another, even smaller percentages end up leading to strong segregation within the residential space.

An experiment will be repeated with different ratios of tolerance from the individual cells to observe if and how they end up segregating within the map.

At 50% ratio, the map seems to be segregated though not as much as when obstacles are added.

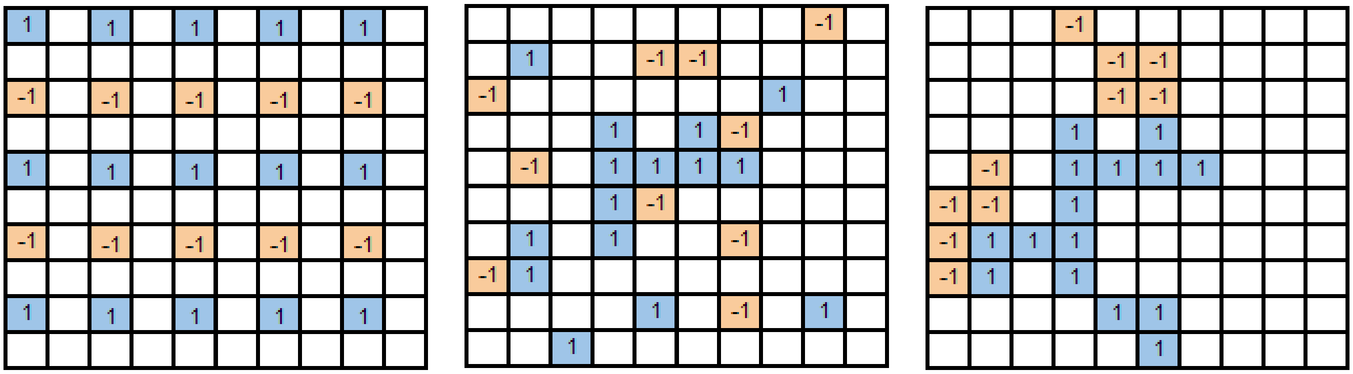


Initial state (t=0) *Intermediate state (t=10)* *Final state (t=499)*

Figure 8: *50% tolerance ratio*

4.7. 25% ratio Experiment

At a 25% ratio, there is no observable difference to the 50%. The final state on figure 9 looks even more segregated than the 50% ratio map, due to the randomness of the moves.

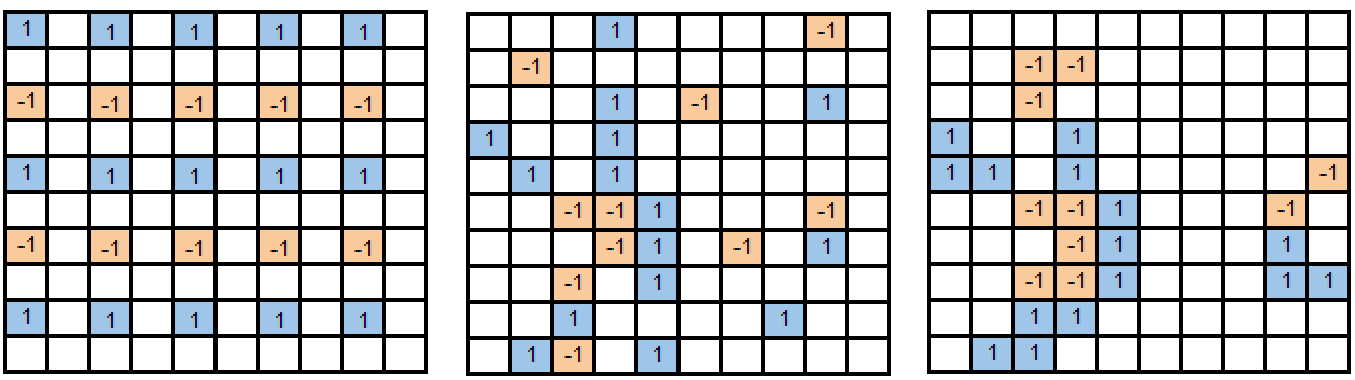


Initial state (t=0) *Intermediate state (t=10)* Final state (t=499)

Figure 9: *25% tolerance ratio*

4.8. 10% ratio Experiment

Lastly, the 10% ratio seems to differ slightly from the other two: While cells are still segregating, there is much more proximity in the groups that they end up forming as can be seen in the final state of figure 10.



Initial state (t=0) *Intermediate state (t=10)* *Final state (t=499)*

Figure 10: *10% tolerance ratio*

5. Conclusions

Through the modeling and simulation of residential segregation using Cell-DEVS and Asymmetric Cell-DEVS, we have demonstrated how simple individual behaviors, when repeated across a population, can give rise to strong and persistent segregation patterns. The experiments presented confirmed that even mild preferences for similar neighbors, as theorized by Thomas Schelling, can ultimately lead to large-scale spatial separation, even when initial conditions seem relatively tolerant.

Using the basic Cell-DEVS model, we replicated the fundamental idea that local dissatisfaction prompts movement, resulting in clustering of similar agents over time. Extending this with Asymmetric Cell-DEVS introduced greater complexity and realism into the model, allowing for diverse behaviors such as varying tolerance thresholds, minimum stay durations, the presence of valuable locations, and the influence of physical obstacles like walls or highways. These enhancements provided a richer understanding of how real-world factors such as infrastructure and property value can further intensify or moderate segregation dynamics.

The experiments revealed several important insights. First, the addition of obstacles significantly reinforced segregation by creating physical divides that limit interaction across groups, simulating real-world phenomena such as segregation along transportation corridors like highways, or natural barriers like rivers. Second, the inclusion of valuable locations introduced nuanced decision-making: residents were sometimes willing to tolerate unfavorable neighborhood compositions in exchange for higher quality living conditions, mirroring the real-world compromises people make in urban settings. Third, even when individuals were modeled as highly tolerant (with thresholds as low as 10% dissimilar neighbors), noticeable segregation still occurred over time, highlighting the powerful, often invisible mechanisms driving societal division.

Overall, the use of Cell-DEVS and Asymmetric Cell-DEVS for segregation modeling proved highly effective. The nature of these models allowed for more realistic simulations of individual decision-making and spatial evolution. The project confirms that decentralized, localized actions can unintentionally create systemic outcomes and emphasizes the importance of understanding micro-level behaviors when designing interventions aimed at reducing segregation.

This work sets the stage for future extensions, such as introducing economic mobility, dynamic neighborhood evolution, or policy interventions (e.g., subsidies for integration) into the model. Further exploration could also involve calibrating the model with real-world data from urban centers to better quantify the impact of different parameters on segregation outcomes.

6. References

[1] T. C. Schelling, “Dynamic models of segregation,” *Journal of Mathematical Sociology*, vol. 1, no. 2, pp. 143–186, 1971.

[2] G. Wainer, *Discrete-Event Modeling and Simulation: A Practitioner’s Approach*, Boca Raton, FL, USA: CRC Press, 2009.

[3] Wikipedia contributors, “Moore neighborhood,” *Wikipedia, The Free Encyclopedia*. [Online]. Available: https://en.wikipedia.org/wiki/Moore_neighborhood

[4] M. Veldhuis, “Society, segregation and science,” *Delta*, Delft University of Technology, Apr. 11, 2024. [Online]. Available: https://delta.tudelft.nl/en/article/society-segregation-and-science