DENSITY WAVES IN CROWD ASSEMBLIES: EMERGING PATTERNS AND AGENT BASED MODELING

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ABSTRACT

The aim of this study is to explore density waves possibly appearing in crowd assemblies through an agent based modeling approach. Emerging patterns of these waves are expected to appear, starting to depend on initial and boundary conditions, where behaviors from the crowd are also critical aspects driving the evolution dynamics. A 2-dimensional square domain is modeled in the NetLogo platform, suitable for studying Complex Systems like the one under examination, with perimeter boundaries representing initial physical barriers that may be removed with different configurations under some specified circumstance. A crowd of people gathers inside at the start, with variable initial densities set to explore different initial conditions. By the time the movements in the crowd, driven by some event (i.e. reaching some spot for increasing entertainment or for escaping perceived critical situations), significantly vary the density (persons per square meter) from lesser global density values to higher local density values, patterns of pressure waves move through the assembly. The behaviors of the people as individual (from reactive to adaptive) define the contact pressures among the persons, where upper thresholds that may be tolerable become critical parameters. As a consequence, the people's behavior as a whole translates into the pressure density waves propagation. Suitable metrics and behavioral rules are adopted in order to represent and verify the evolution dynamics, where clusters of density and overcrowded situations are counteracted or avoided by pulses of action helping recover to better conditions (i.e. way-out through gradient-following or field attractors, proper communication effects trying to reduce emotional contagion).

Keywords: complex adaptive systems, agent based model, behavior, emerging pattern

1 INTRODUCTION: COMPLEX SYSTEMS AND THE ODD PROTOCOL

This study is part of the update in our research programme for exploring Crowd and Fire Dynamics in their essence of Complex Systems, where the interactions of the single entities in the system may let emerge patterns of behavior of the overall set [1][2][3].

To this end, we adopt the Agent Based Modeling (ABM) approach by means of the NetLogo platform, suitable for studying Complex Systems like the one under examination [4][5][6]. The aim of this study is to explore density waves possibly appearing in crowd assemblies, where some kind of emerging patterns of these waves are expected to appear, starting to depend on initial and boundary conditions. In NetLogo, a 2-dimensional square domain is thus modeled, with perimeter boundaries representing initial physical barriers that may be removed or not, with different configurations under some specified circumstance. A modeled crowd of people gathers inside at the start, with variable initial densities set up to explore different initial conditions. By the time the movements in the crowd, driven by some event (i.e. reaching some spot for increasing entertainment or for escaping perceived critical situations), significantly vary the density (persons per square meter) from lesser global density values to higher local density values, patterns of pressure waves may start and develop through the assembly. The behaviors of the people as individual (from reactive to adaptive) define the contact pressures among the persons, where upper thresholds that may be tolerable become critical parameters. As a consequence, the people's behavior as a whole translates into the pressure density waves propagation. Suitable metrics and behavioral rules are adopted in order to represent and track the evolution dynamics, where clusters of density and overcrowded situation are hopefully counteracted or avoided by pulses of action helping people recover to better conditions (i.e. shifting to near places where reduction of density to lower levels is allowed, way-out through gradient-following or field attractors, proper communication effects trying to reduce emotional contagion).

The following ODD (Overview, Design concepts, Details) protocol describes briefly the features of the NetLogo model in a synthetic manner.

The Overview: the approach of ABM – sometimes also referred to as Multi Agents System (MAS), albeit with slightly different definitions irrelevant here – is adopted to model and explore some possible variations of appearance of the complex system under examination due to the interactions of the elements involved. This approach makes it also possible to investigate the interactions that may intuitively be expected to appear, stabilise and disappear, often with sudden transitions due to some thresholds in critical parameters, where sometimes finding the existence of those kind of critical parameters is one task of the modeling itself. Furthermore, each agent will possibly have its own internal different state and some effect of the internal state of the agent could be coupled with the state of the environment. The model tries to explore the emergence and the evolution of crowd density waves. The waves develop while the contact pressure among the persons over a unit area begins to increase and no relief to reduce the pressure is quickly available. The persons come into contact, ever increasing into a same unit area due to some event, thus shifting toward or remaining inside some area insufficient to collect them at a comfortable level. The only way to stop pressure from increasing is either limiting the number of persons per unit area or let some persons quickly move away from the overcrowded area, once the event triggers the onset of the wave.

The Design concepts: the model aims at studying some basic aspects of this complex system – such as interaction, adaptation, stochasticity – and then characterising some of its typical properties – such as emergence, self-organisation, co-evolution [7]. We use two NetLogo agentsets: the patches for modeling the world and the turtles for modeling the people. The world represents the environment the people are in; it is modeled at the setup with its perimeter boundaries on the sides as solid barriers that are closed since the start. A comparison is then made with the boundaries that may be either always left closed or opened at some time during the simulation run, with the opening preferably activated through some kind of adaptation to the local level of density. The patch is the space unit to move on in the world; each patch is a square unit, whose dimension is always setup as one square meter, with side length of one meter (1 m^2 area and 1 m side length patch unit). This dimension for the patches helps us in the adoption of suitable metrics. The number of patches in the world may be let vary, with increased side of the world, but each patch is always 1 m^2 area and 1 m side. To this dimension unit the crowd density is related (persons per square meter [p/m^2]). Depending on the number of persons over a patch, a global density is initialised in the world. When the number of persons over a patch increases, the patches' colors vary in accordance to let appear the way the density changes, so that local density is also tracked. The density wave emergence can thus be tracked as the evolution of the colors in the patches. The turtles model the crowd, each turtle modeling a person. The shape of the turtle can be varied depending on the goal: the default arrow to highlight heading, the dot to highlight position, the person to highlight the human shape.

The Details: initialisation, input data, sub-models. The model is initialised by designing the environment and the agents. No recorded data are used to start the model, some estimations are made from personal experience and literature survey instead. The environment represents a two-dimensional plane open square, where the perimeter boundaries may be in to states: closed (the agents cannot trespass) or open (the agents can move through). The agents represent the people inside the square, where their position is initially randomly set to model a starting global crowd density. The input data of the environment are the geometry (plan area, side dimensions, perimeter boundaries) and the effects (boundaries closed or open). The input data of the agents are the position (number, spatial distribution) and the characteristics (physical and cognitive). The sub-models refer to the actions of the agents (movements and decisions), either reactive or adaptive, and to the effects of the environment (perimeter boundaries states).

2 NETLOGO: BEHAVIORAL RULES AND CONSTRAINTS

In order to describe the behavioral rules of the agentsets of the system it is convenient to adopt an agent-centric viewpoint: a particular useful mindset where the rules are described as seen by the agent, not by an external observer. The rules are quite a few, just needed for starting actions and activate reactions or adaptations, with the intent and hope of letting the system evolve by itself to some state with some pattern that may emerge as observable. We refer, of course, to some kind of pressure density wave patterns due to the contact in the people of the crowd in the environment during the evolution dynamics of the system. So, *if I am a patch*: I help set the world, its domain side, internal area and perimeter boundaries; I am always a 1 m^2 square independently of the domain side chosen, so a suitable metric may be devised; when representing a boundary, my state can be closed or open, and I have an option of adapting my opening to some effect due to the turtles; I can always accept turtles on me; I set and change my color depending on the number of turtles on me, up to a limit threshold. And, *if I am a turtle*: I model a single person; I can move or not move, also changing my heading; I may get closer and closer to other turtles on a same patch, up to a limit threshold of the number of turtles that may be on a same patch in the same time window; if I behave as reactive, my action depends primarily to some event occurred in a past time that may have affected me; if I behave as adaptive, my action depends both on some past event and on some choice or forecast I make to try to get to a better future condition for myself.

Once decided the setup (the world with patches and turtles to run the simulation), the model is programmed in such a way to: code the rules, design and apply proper control tools in the NetLogo interface for managing any operation needed and visualizing the results. The metrics, devised to analyse data, compare results and explain outputs, are based on a continuous space and discrete time frame. Several runs of a same baseline setup are needed to take into account, at least in a basic form, stochastic effects linked to the system.

The first type of setup is prepared to study the emergence of density waves in the form of longitudinal pressure waves, where the contact among the persons appears along some preferential direction. The second type of setup is prepared to study the emergence of density waves in the form of radial pressure waves, where the contact among the persons appears as related to a central spot. In both cases, the model tries to take into account if some critical parameter that may characterise the response of the system to inputs and noise may appear (i.e. clusters of sudden increased local density, available spots to relieve overpressures, trends of variation in the density). Furthermore, the model tries to take into account if some threshold marking a sudden onset of changing in the response of the system comes into play (i.e. average local density jump or fall, percentage of dangerous areas in the domain). Some metric may then be devised based on those critical parameters and thresholds.

In order to get started for the model, the NetLogo dashboard interface is properly prepared for this study using many of the specific tools available (some require only an updating to the model to be run, yet some require specific programming):

the setting of the world (coordinate system, number of patches, state of the perimeter boundaries, time unit advancement);
the dimension of the world (length of the square domain side, area of the domain);
the time unit length of the simulation run (ticks to stop – the tick is the discrete time unit clock: the simulation run advances of one tick whenever all of the agents involved have performed their task);
the turtle's shape (arrow, dot, human);
the number of turtles to be randomly assigned per patch (in order to obtain the desired initial global density with the total turtles set at the start);
some alternative to choose for some turtle's behavior (i.e. forming clusters, chance of recovering);
turtles possibly involved in some starting action (percentages on the total number of the initial turtles set);
alternative to rendering either the density waves or the people's moves in the domain (colored patches or turtles);
setting of some threshold for the crowd density (actions to be performed by the turtles either possible or stop for the simulation);
setting of the possible available state of the boundaries (reactive on command or adaptive on the evolution dynamics, density thresholds for adaptive behavior);
some monitors to get dynamically variable information during the simulation run (total patches, domain side, total turtles, global density, number of the different colored patches, sum of all patches, average local density, percentage of overcrowded areas);
some 2D-plots that may dynamically vary to show some trend (plots auto-scaling: number of turtles inside the domain over ticks, average densities over ticks as type 1 metric, percentage of overcrowded areas over ticks as type 2 metric).

3 SIMULATIONS: EMERGING PATTERNS

The model for studying the possible emergence of patterns for *longitudinal pressure waves* shows the following characteristics, here referred to the 2D-domain square of 100 m sides (yet the model can quickly let vary the domain side by a proper resizing programmed tool placed in the dashboard and linked to the script coded):
the world is initialised as a square with 100 m side length and perimeter boundaries closed, defined by 100 x 100 square patches 1 m side 1 m^2 each; by randomly choosing a variable number of patches that may generate a random number of new turtles on them in a proper limited range, the turtles in the world are inserted with random headings. By combining the number of patches that generate turtles and the number of turtles sprouted, a global density of turtles per patch in the world is set, meaning a crowd global density of persons per square meter [p/m^2] is set at the start. Two initial global densities are chosen: 2 [p/m^2] and 1 [p/m^2], to run the simulations. Depending on the initial turtles per patch obtained, the patches are colored in consequence: white patches with 0 turtles on, green patches with 1 turtle on, yellow patches with 2 turtles on, orange patches with 3 turtles on, red patches with 4 turtles on, magenta patches with > 4 turtles on up to a limit that can be varied to study different conditions. This initialises also the local densities and will bring to the average local density as one metric and to the limit average local density as one critical parameter that will stop the simulation. It is worth-noting that the automatic patch coloring is updated at every tick during the simulation advancement, with two important consequences: one) the variation in the colors of the patches shows the variation in the local density and so the emerging pattern of the density wave, two) the reaching of the limit average local density stops the simulation. Proper tools placed in the dashboard interface help initialising the world, setup and run the simulations. Other tools are placed to monitor and plot a number of information both at setup and during the simulation run, such as: monitors for counting (total patches, domain side, total turtles, global density, white patches, green patches, yellow patches, orange patches, red patches, magenta patches, sum of all patches, average local density), plots for control (total turtles in the domain), plots for metric (average densities, overcrowded areas). The simulation is almost ready to go, but now what are the basic rules of behavior adopted for patches and turtles? Let's have a look at them, considering the simulations where the turtles can both move and recover, thus exploring also the possibility of getting to a better suited final state by some action. The simulations could also be run with the option where the turtles only move without recovering: this could be useful for studying what types of movement might be modeled first, before adding the part of model for recovering.
I am a patch: at setup I start forming the world and sprout turtles on me at random in a defined range thus defining what color I'm initialised with; during the run I update my color that may vary depending on the number of turtles on me.
I am a turtle: at setup I'm sprouted on some patch with some heading, I might have some other turtle on the same patch I'm on; during the run I may move in the first half of the simulation runtime, then recover in the second part of the simulation runtime; if I belong to the group of turtles starting the action of moving, I set my heading aligned on one preferred direction set, then if I am not on a border patch that limits the world in the direction I'm heading and see some space on the next patch ahead (up to four turtles on) I randomly vary very slightly my heading and move forward randomly near to that patch; if recovering is allowed and I belong to the group of turtles starting the action of recovering, I reverse my heading then, if I am on a border patch that limits the world in the direction I'm heading or I see no more than a few (up to two) turtles on the next patch ahead I stop, thus letting develop sufficient room ahead, otherwise if I see not many more (no more than three) turtles on the next patch ahead I randomly vary very slightly my heading and move forward to that patch.
Through these rules of behavior, it is hoped to let emerge and observe in the simulation some pattern of the density waves. The following Table 1 shows the actions of the agents and the rules of behavior for the longitudinal pattern.

Table 1: Longitudinal patterns - Behavioral rules for actions

Longitudinal Waves Emerging Patterns		
Action	*Agentset*	*Behavior*
Setting the world	Patches	Initialisation of the geometry, sprouting of the turtles, local density mapping
To move	Turtles	First half of simulation runtime window – Set of heading, wiggle and move forward or stop
To recover	Turtles	Second half of simulation runtime window – Reverse of heading, wiggle and move forward or stop
Density wave rendering	Patches	Updating local density mapping

The model for studying the possible emergence of patterns for *radial pressure waves* shares the same characteristics of the model for studying the longitudinal waves, with a few specific differences, here briefly summarised and referred to the same 2D-domain square of 100 m sides (yet the model can again quickly let vary the domain side by a proper resizing programmed tool placed in the dashboard and linked to the script coded).
The same characteristics are: initialisation of the world (100 m side length square domain, perimeter boundaries closed, 100 x 100 square patches 1 m side 1 m^2 each, random sprouting of turtles per patches with random headings, two global densities possible of 2 and 1 persons per square meter, colors of patches depending on the local density of turtles per patch); tools on the dashboard interface (monitors and plots), metrics (average local density, up to a limit that will stop the simulation; percentage of overcrowded areas), runtime clock (ticks to end of simulation), updating during run (colors of patches, data on monitors and plots), intention of actions (move, recover).
The few differences are: patterns of simulation (form-clusters, move-clusters) and some behavioral rules (patches, turtles). Let's have a look at them: the possibility of forming clusters of turtles in some part of the domain is now linked to the way the turtles may collect or spread, during the simulation runtime coded, to move and to recover to a preferable final state. The behavioral rules now highlight also the possibility of increasing the level of adaptation to better help turtles escape from the overcrowded spaces; here they are as described by the agents:
I am a patch: at setup I start forming the world and sprout turtles on me at random in a defined range thus defining what color I'm initialised with, if I live on the boundaries I may change the state of the boundary from closed to opened, letting escape the turtles out of the world; during the run, if I live on the boundaries I have the option of letting the boundaries be opened, either from the first tick of run or whether a local density on me exceeds a threshold set in advance; furthermore I update my color that may vary depending on the number of turtles on me.
I am a turtle: at setup I'm sprouted on some patch with some heading, I might have some other turtle on the same patch I'm on; during the run I may move in the first half of the simulation runtime, then recover in the second half of the simulation runtime, and I also may form clusters with other turtles; if I belong to the randomly chosen group of turtles starting the action of forming clusters, I set my heading toward one patch in the part of the world the cluster is meant to form and, if I see some space on the next patch ahead (up to three turtles on), I randomly wiggle and move a little forward; otherwise, if I don't belong to the group of turtles that start forming clusters but belong to another randomly chosen group of turtles, I very slightly wiggle and move a little forward at random; then for the action of moving clusters, if I'm on a patch with a little space available (more than three turtles on) I wait a little then I reverse my heading and move to the patch ahead, otherwise if I'm on a patch with more space available (up to three turtles on) I very slightly move forward and wiggle at random; in addition, if it is allowed to have the boundaries free in the recovery phase of the simulation, I may adapt to quickly escape from the world if I'm on a patch on the boundaries; even better, with adaptive boundaries I may adapt to quickly escape from the world if: I'm on a patch on the boundaries, there are still patches in the domain with very little space available (more than five turtles on) and the number of turtles on the patch I'm on is equal or greater than the local density threshold set in advance, thus allowing escape independently of the phase of the simulation.
Through these rules of behavior, it is hoped to let emerge and observe in the simulation some pattern of the density waves. The following Table 2 shows the actions of the agents and the rules of behavior for the radial pattern.

Table 2: Radial patterns - Behavioral rules for actions

Radial Waves Emerging Patterns		
Action	*Agentset*	*Behavior*
Setting the world	Patches	Initialisation of the geometry, sprouting of the turtles, local density mapping
To form-clusters	Turtles	First half of simulation runtime window – Set of heading, wiggle and move forward or stop
To move-clusters	Turtles	Second half of simulation runtime – Reverse of heading, wait, wiggle and move forward or stop
Density wave rendering	Patches	Updating local density mapping
Escape from the world	Patches	Updating local density mapping
Escape from the world	Turtles	Check of patches and local density threshold, die

For both types of emerging patterns, longitudinal and radial, several simulations were performed based on these actions and rules. Groups of four simulations were used, each based on a similar initial setup but with four different runtime windows of 100, 300, 500 and 1000 ticks, and global density on average of 2 p/m^2 or 1 p/m^2. Some slight differences appear for each group in the initial setups and in the results, due to the random actions coded (i.e. sprouting of turtles) and the overall evolution dynamics. Any of these related four simulations show how the emerging patterns of the density

waves may vary, starting from substantially similar conditions, depending on the effects on the system of the single actions performed by the agents involved in function of the runtime clock available.
The following Tables 3 to 6 show some results obtained from the simulations.

Table 3: Longitudinal patterns – Some results from simulations 1 to 8

Longitudinal Waves Emerging Patterns							
Simulation	Runtime clock	Simulation end	Domain Area	Turtles start	Turtles end	Overcrowded Area end	Average Local Density end
Initial global density of 2 p/m ^{2} with 20000 persons in the 100 m side square domain with boundaries closed							
1	100 ticks	100 ticks	10000 m ^{2}	20072	20072	25.35 %	6.53 p/m ^{2}
2	300 ticks	300 ticks	10000 m ^{2}	19711	19711	23.91 %	6.59 p/m ^{2}
3	500 ticks	500 ticks	10000 m ^{2}	20095	20095	21.76 %	6.56 p/m ^{2}
4	1000 ticks	1000 ticks	10000 m ^{2}	20129	20129	17.01 %	6.55 p/m ^{2}
Initial global density of 1 p/m ^{2} with 10000 persons in the 100 m side square domain with boundaries closed							
5	100 ticks	100 ticks	10000 m ^{2}	10066	10066	10.12 %	6.03 p/m ^{2}
6	300 ticks	300 ticks	10000 m ^{2}	9916	9916	9.74 %	6.12 p/m ^{2}
7	500 ticks	500 ticks	10000 m ^{2}	10058	10058	6.84 %	6.06 p/m ^{2}
8	1000 ticks	1000 ticks	10000 m ^{2}	9997	9997	0.37 %	5.92 p/m ^{2}

Table 4: Radial patterns – Some results from simulations 9 to 16

Radial Waves Emerging Patterns							
Simulation	Runtime clock	Simulation end	Domain Area	Turtles start	Turtles end	Overcrowded Area end	Average Local Density end
Initial global density of 2 p/m ^{2} with 20000 persons in the 100 m side square domain with no escape out from the boundaries							
9	100 ticks	100 ticks	10000 m ^{2}	19947	19947	9.08 %	9.79 p/m ^{2}
10	300 ticks	160 ticks	10000 m ^{2}	19949	19949	11.54 %	10.18 p/m ^{2}
11	500 ticks	201 ticks	10000 m ^{2}	20243	20243	10.39 %	10.06 p/m ^{2}
12	1000 ticks	195 ticks	10000 m ^{2}	19782	19782	10.08 %	10.03 p/m ^{2}
Initial global density of 1 p/m ^{2} with 10000 persons in the 100 m side square domain with no escape out from the boundaries							
13	100 ticks	100 ticks	10000 m ^{2}	9820	9820	2.99 %	9.28 p/m ^{2}
14	300 ticks	173 ticks	10000 m ^{2}	10115	10115	5.33 %	10.06 p/m ^{2}
15	500 ticks	257 ticks	10000 m ^{2}	9983	9983	6.56 %	10.18 p/m ^{2}
16	1000 ticks	306 ticks	10000 m ^{2}	10054	10054	5.94 %	10.00 p/m ^{2}

Table 5: Radial patterns – Some results from simulations 17 to 24

Radial Waves Emerging Patterns							
Simulation	Runtime clock	Simulation end	Domain Area	Turtles start	Turtles end	Overcrowded Area end	Average Local Density end
Initial global density of 2 p/m ^{2} with 20000 persons in the 100 m side square domain with boundaries opened from the second half of runtime only							
17	100 ticks	100 ticks	10000 m ^{2}	19922	14648	6.75 %	6.05 p/m ^{2}
18	300 ticks	300 ticks	10000 m ^{2}	20010	5091	0.41 %	5.39 p/m ^{2}
19	500 ticks	199 ticks	10000 m ^{2}	19989	19989	10.15 %	10.04 p/m ^{2}
20	1000 ticks	198 ticks	10000 m ^{2}	20199	20199	10.44 %	10.00 p/m ^{2}
Initial global density of 1 p/m ^{2} with 10000 persons in the 100 m side square domain with boundaries opened from the second half of runtime only							
21	100 ticks	100 ticks	10000 m ^{2}	10103	7430	0.56 %	5.29 p/m ^{2}
22	300 ticks	300 ticks	10000 m ^{2}	9848	1736	0.04 %	5.00 p/m ^{2}
23	500 ticks	500 ticks	10000 m ^{2}	10027	0	0.00 %	//
24	1000 ticks	309 ticks	10000 m ^{2}	9902	9902	5.95 %	10.00 p/m ^{2}

Table 6: Radial patterns – Some results from simulations 25 to 32

Radial Waves Emerging Patterns							
Simulation	Runtime clock	Simulation end	Domain Area	Turtles start	Turtles end	Overcrowded Area end	Average Local Density end
Initial global density of 2 p/m ^{2} with 20000 persons in the 100 m side square domain with adaptive boundaries 4 p/m ^{2} limit threshold at boundary							
25	100 ticks	100 ticks	10000 m ^{2}	19836	14535	6.70 %	6.14 p/m ^{2}
26	300 ticks	300 ticks	10000 m ^{2}	20078	5200	0.42 %	5.38 p/m ^{2}
27	500 ticks	500 ticks	10000 m ^{2}	20050	1	0.00 %	//
28	1000 ticks	1000 ticks	10000 m ^{2}	20196	0	0.00 %	//
Initial global density of 1 p/m ^{2} with 10000 persons in the 100 m side square domain with adaptive boundaries 4 p/m ^{2} limit threshold at boundary							
29	100 ticks	100 ticks	10000 m ^{2}	9990	7311	0.57 %	5.30 p/m ^{2}
30	300 ticks	300 ticks	10000 m ^{2}	10000	1803	0.01 %	5.00 p/m ^{2}
31	500 ticks	500 ticks	10000 m ^{2}	9867	0	0.00 %	//
32	1000 ticks	1000 ticks	10000 m ^{2}	9981	0	0.00 %	//

The following Figures 1 to 16 show some snapshots from the dashboard of the results obtained at the end of the runtime elapsed for the simulations with 100 ticks and 1000 ticks of runtime clock.

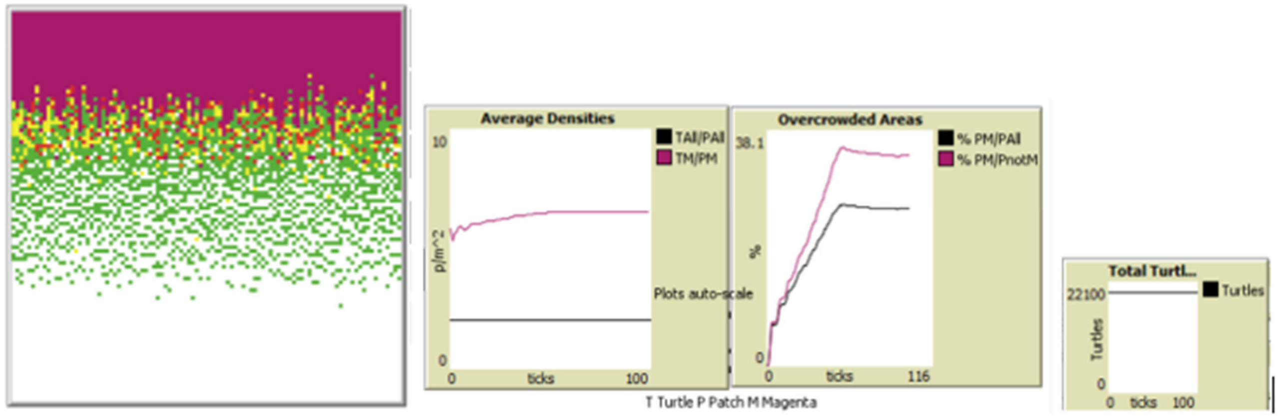

Figure 1 Simulation 1 at 100 ticks end of run completed

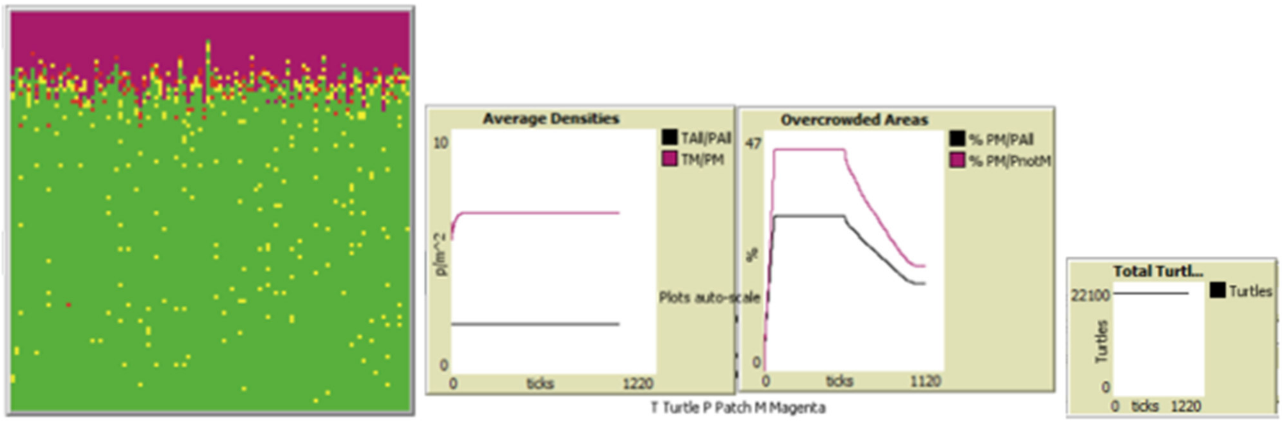

Figure 2 Simulation 4 at 1000 ticks end of run completed

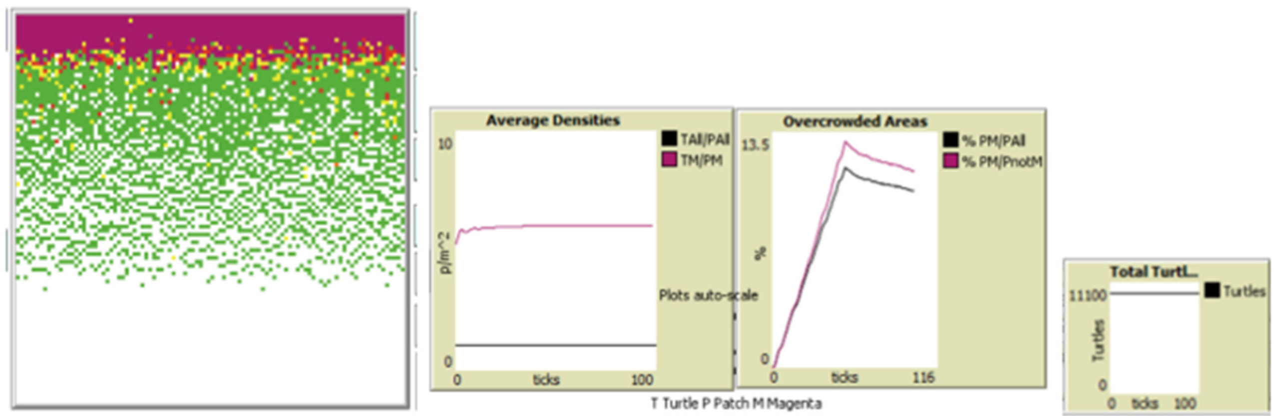

Figure 3 Simulation 5 at 100 ticks end of run completed

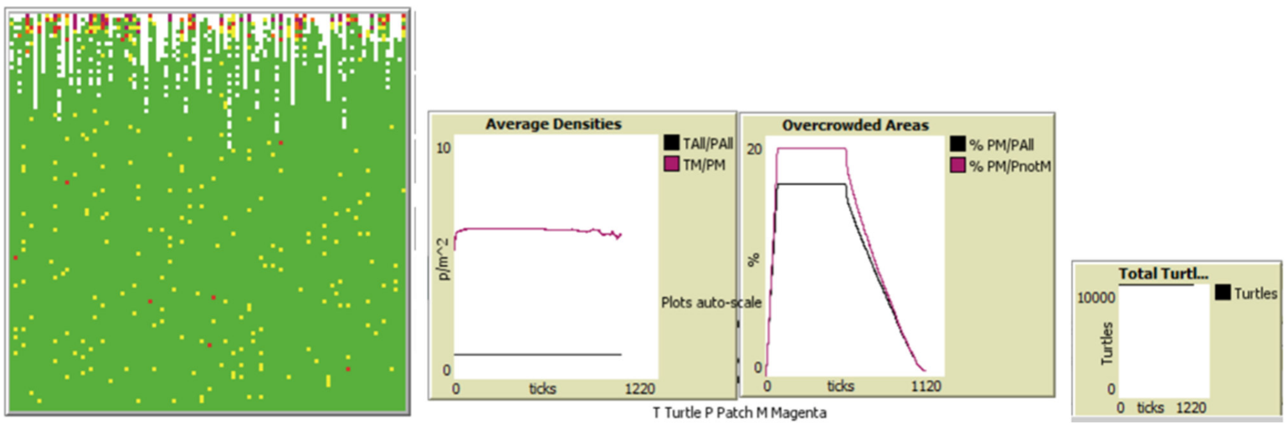

Figure 4 Simulation 8 at 1000 ticks end of run completed

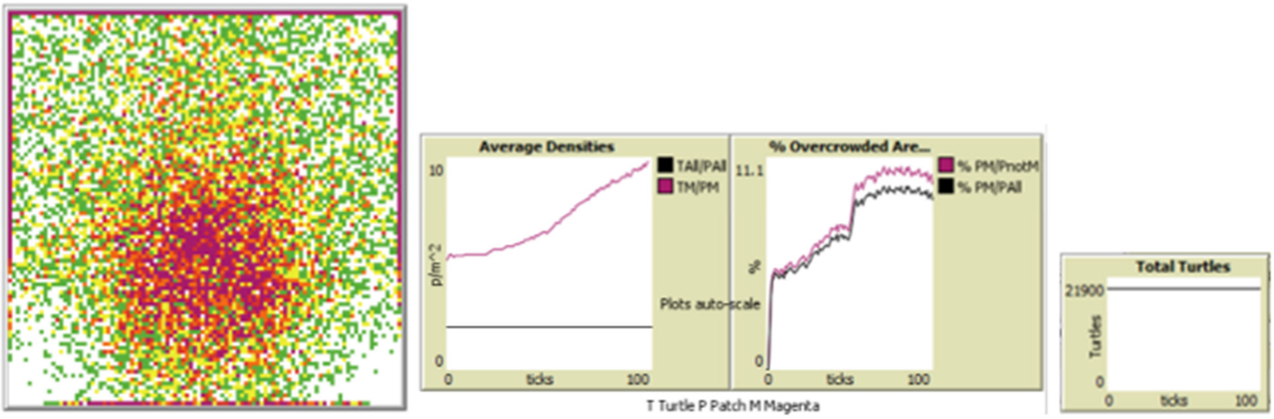

Figure 5 Simulation 9 at 100 ticks end of run completed

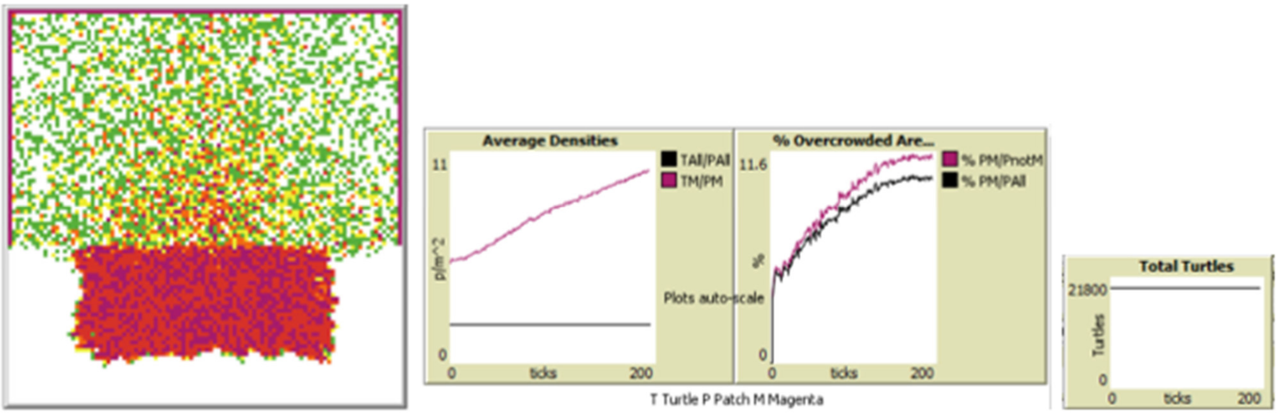

Figure 6 Simulation 12 at 135 ticks instead of 1000 end of run stopped

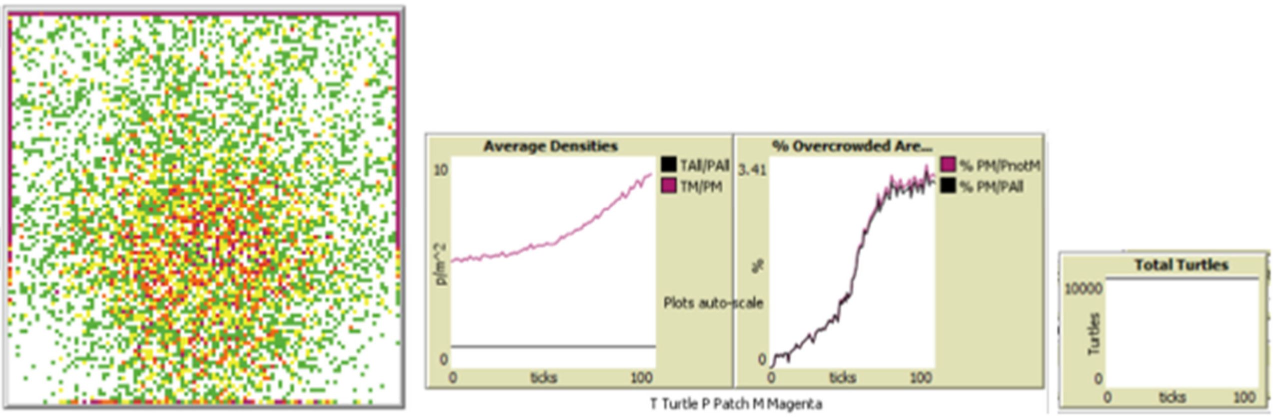

Figure 7 Simulation 13 at 100 ticks end of run completed

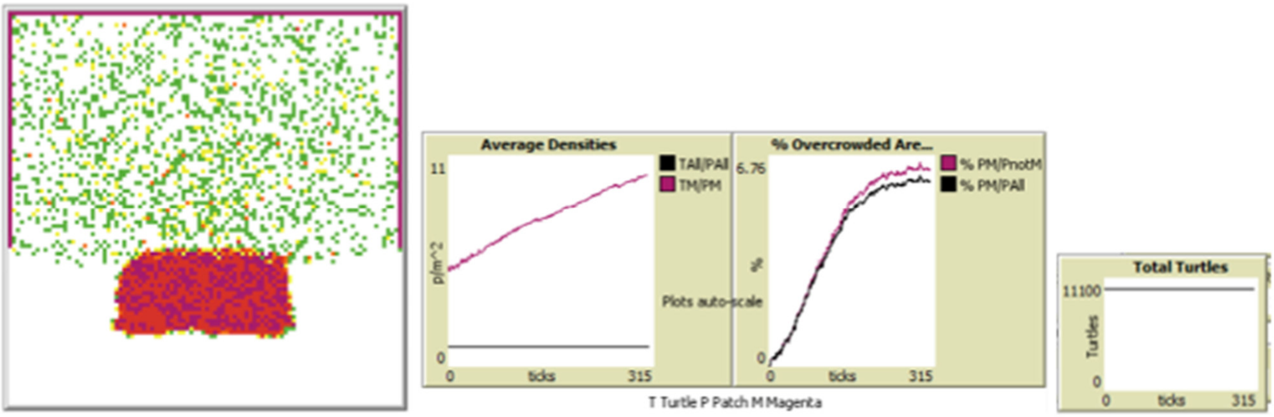

Figure 8 Simulation 16 at 306 ticks instead of 1000 end of run stopped

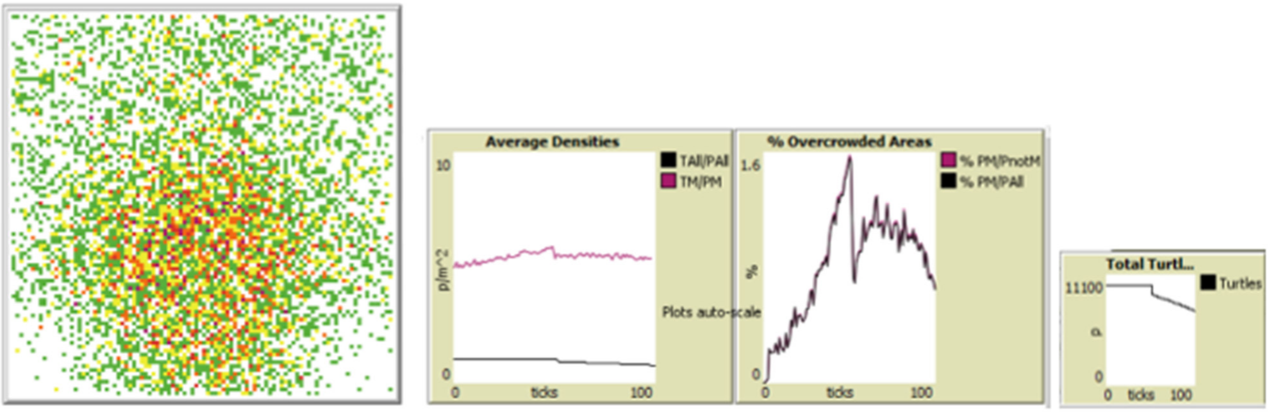

Figure 9 Simulation 17 at 100 ticks end of run completed

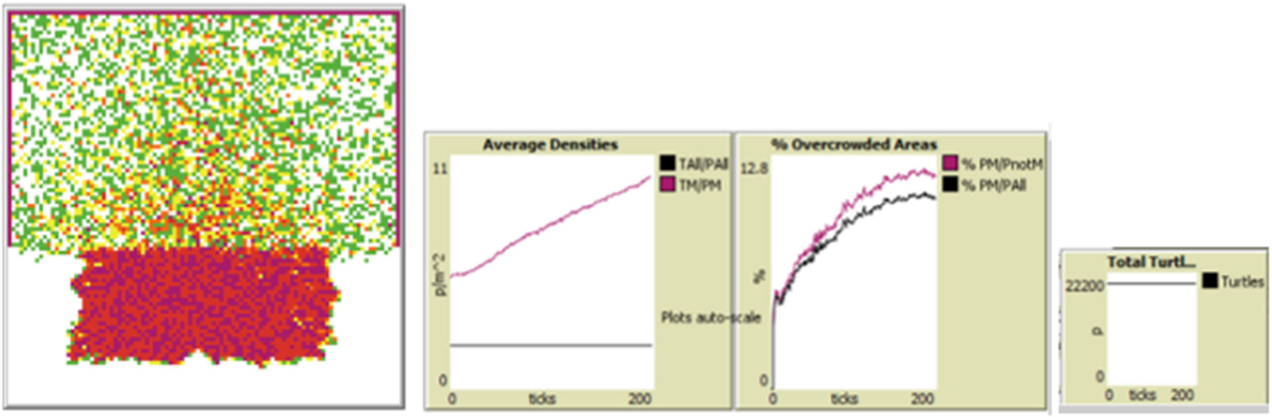

Figure 10 Simulation 20 at 198 ticks instead of 1000 end of run stopped

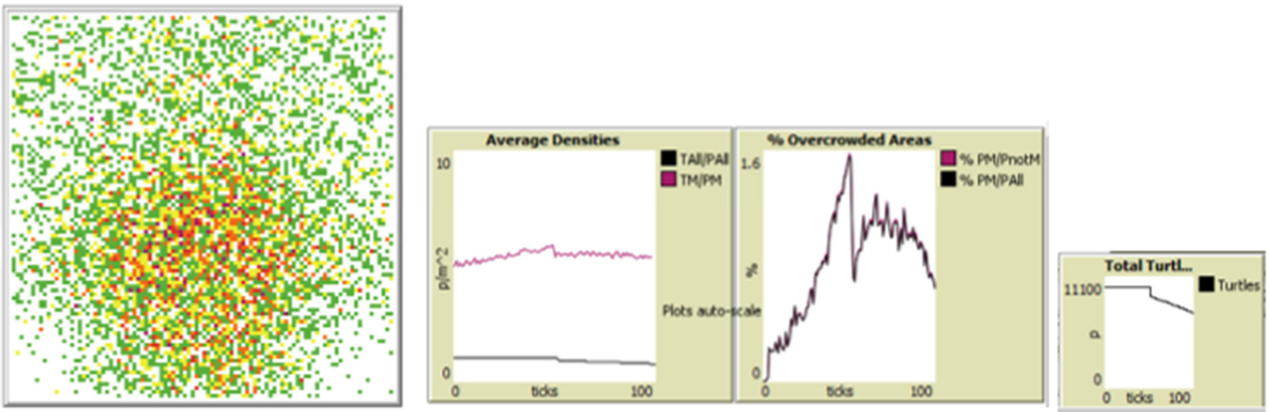

Figure 11 Simulation 21 at 100 ticks end of run completed

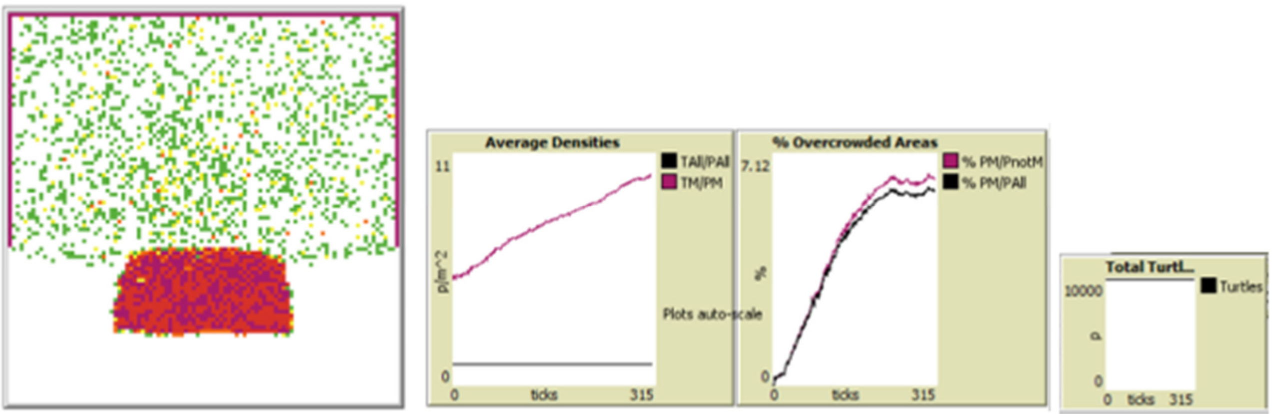

Figure 12 Simulation 24 at 309 ticks instead of 1000 end of run stopped

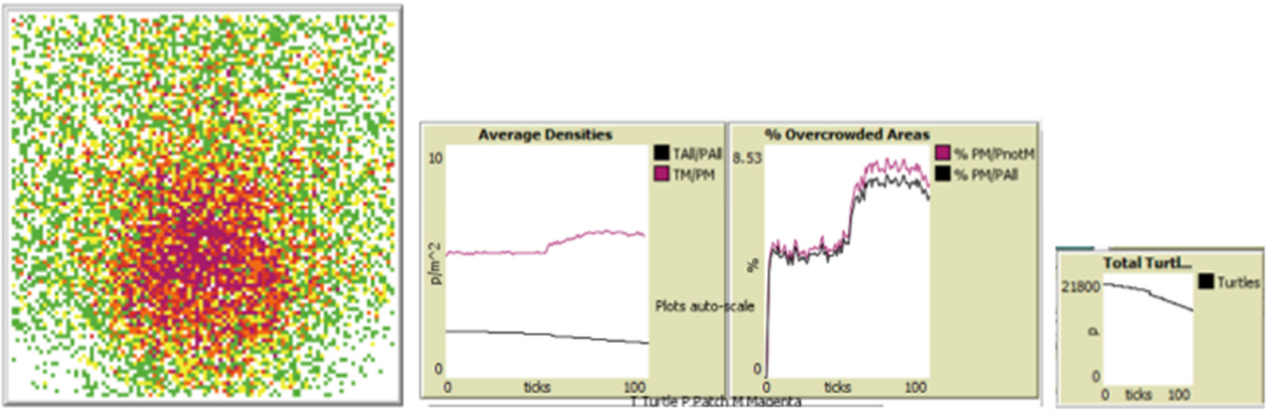

Figure 13 Simulation 25 at 100 ticks end of run completed

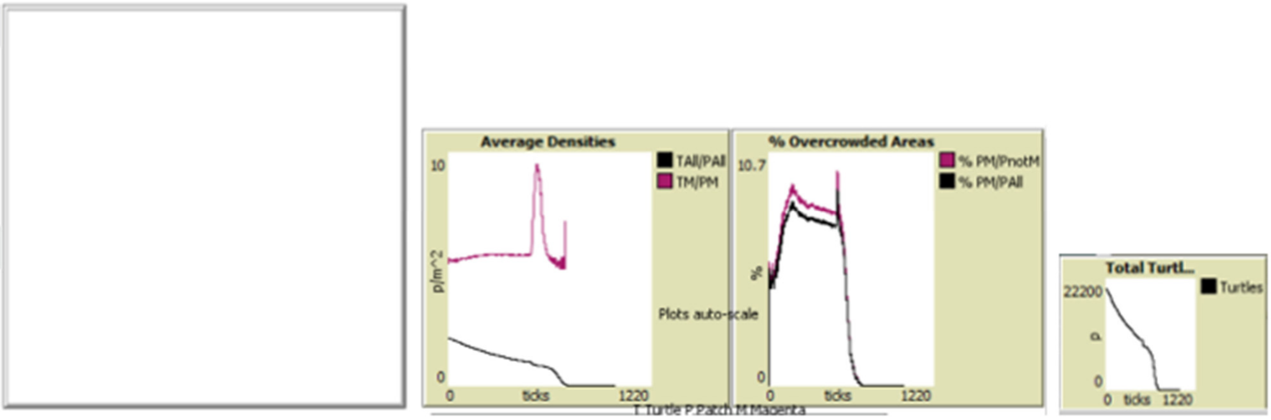

Figure 14 Simulation 28 at 1000 ticks end of run completed

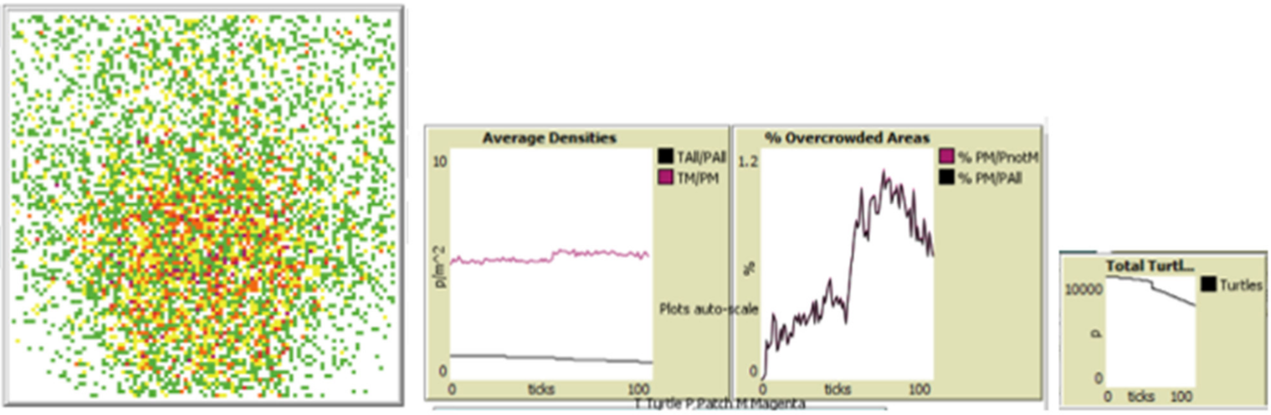

Figure 15 Simulation 29 at 100 ticks end of run completed

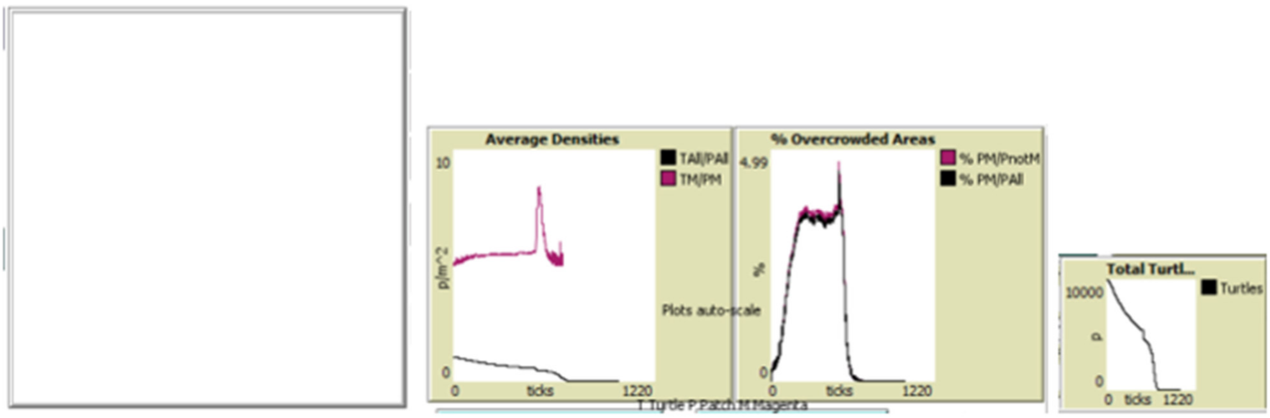

Figure 16 Simulation 32 at 1000 ticks end of run completed

In order to show some shape of the evolution dynamics of the emerging patterns of the simulations, the following Table 7 and Figures 17 to 20 show some results and snapshots from the dashboard of the results obtained at a sequence of the time advancement of the runtime elapsed for the same simulations with 1000 ticks of runtime clock.

Table 7: Longitudinal and Radial patterns – Some results from simulations 33 to 36

Longitudinal and Radial Waves Emerging Patterns							
Simulation	Runtime clock	Simulation end	Domain Area	Turtles start	Turtles end	Overcrowded Area end	Average Local Density end
Longitudinal Waves Emerging Patterns							
Initial global density of 2 p/m^2 with 20000 persons in the 100 m side square domain with boundaries closed							
33	1000 ticks	1000 ticks	10000 m^2	20000	20000	16.74 %	6.55 p/m^2
Initial global density of 1 p/m^2 with 10000 persons in the 100 m side square domain with boundaries closed							
34	1000 ticks	1000 ticks	10000 m^2	10101	10101	0.59 %	5.75 p/m^2
Radial Waves Emerging Patterns							
Initial global density of 2 p/m^2 with 20000 persons in the 100 m side square domain with adaptive boundaries 4 p/m^2 limit threshold at boundary							
35	1000 ticks	1000 ticks	10000 m^2	19985	0	0.00 %	//
Initial global density of 1 p/m^2 with 10000 persons in the 100 m side square domain with adaptive boundaries 4 p/m^2 limit threshold at boundary							
36	1000 ticks	1000 ticks	10000 m^2	9933	0	0.00 %	//

Figure 17 Simulation 33 at ticks 0-25-499-700-1000

Figure 18 Simulation 34 at ticks 0-25-499-700-1000

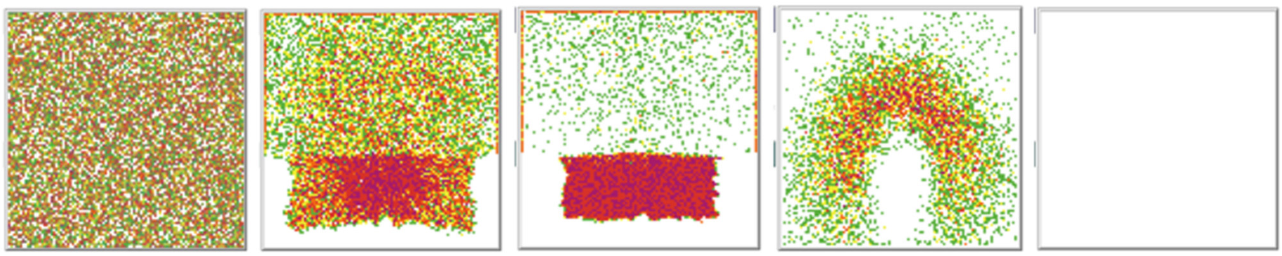

Figure 19 Simulation 35 at ticks 0-100-499-600-1000

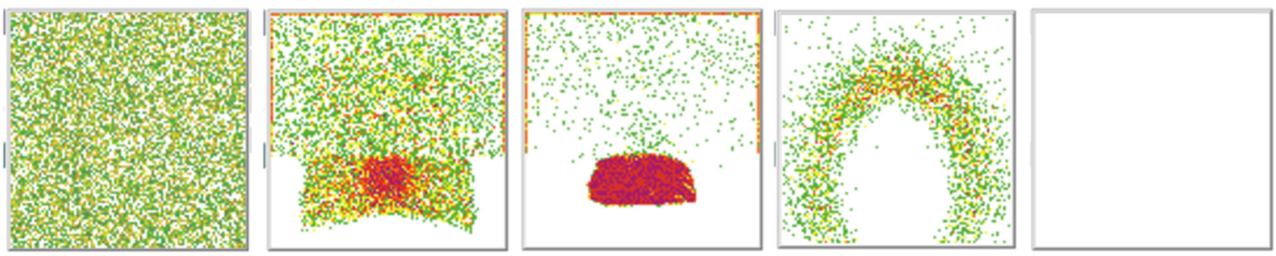

Figure 20 Simulation 36 at ticks 0-100-499-600-1000

4 CONCLUSION AND FUTURE WORK

The model was able to let patterns emerge in all of the simulations, with characteristics of development depending on the initial setup and the interactions in the system during the runtime. Some parameters show a greater effect on the results than others. In particular, the initial global density, the time the boundaries can get opened and the limit average density threshold mostly affect the results. The metrics show overall trends and sudden changes in the evolution dynamics of the system. Future work is scheduled to expand the groups of simulations and examine in detail similarities and differences, and to examine the effect of critical parameters as input (i.e. initial density, boundaries opening, density threshold) and output (i.e. metrics).

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