

DATA DRIVEN MODELING AND SIMULATION ABOUT CARP AGGREGATION

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ABSTRACT

Asian carp is notorious as one of the most severe aquatic invasive species (AIS) threats to the waters of the Mississippi River Region. The devastating effect of Asian carp calls for desperate measures to decrease the spread of Asian carp and prevent possible invasion into the Great Lake. This work presents an agent-based mathematical model to simulate the aggregation of Asian carp which would provide valuable help in fish removal or control. The referred mathematical model is derived from the following assumptions: (1) the aggregation results from a completely random and spontaneous physical behavior of numerous independent carp rather than consensus among every carp involved in the aggregation; (2) carp aggregation is a collective effect of inter-carp and carp-environment interaction; (3) aggregation happens when two carp or two schools of carp approach each other within a perceptible distance. As a variant of the molecular dynamics method, the proposed mathematical model is based on an empirical inter-carp force field which is featured with repulsion, parallel orientation and attraction zone. Besides, due to the physical limitation of carp, we also considered out-of-perception zone and a blind zone. By employing an inter-carp force field, the aggregation behavior of carp is investigated. Preliminary simulation results about the aggregation of a small number of carp within a simple environment are provided. Further experiment-based validation about the mathematical model is also briefly discussed and further suggested as possible future work.

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TABLE OF CONTENTS

ABSTRACT.....	iii
ACKNOWLEDGEMENTS.....	iv
LIST OF FIGURES	vii
LIST OF ABBREVIATIONS.....	ix
LIST OF SYMBOLS	x
CHAPTER	
1. INTRODUCTION	1
1.1 Overview	1
1.2 Asian Carp.....	2
1.2.1 Diet and Life History	4
1.3 Lessons and Impacts.....	5
1.3.1 Potential Risk to the Great Lakes Basin	5
1.3.2 Ecological and Biological Risk	6
1.3.3 Financial Risk.....	7
1.3.4 Social Risk.....	8
1.4 Control Strategies.....	9
2. MODEL ESTABLISHMENT	13
2.1 Background	13
2.2 Model establishment	16
2.2.1 Interaction between neighbouring carp	18
2.2.2 Interaction of Carp without Blind-Zone	19
2.2.3 Interaction of Carp with Blind-Zone	22
2.2.4 Higher-order Interaction	24
2.3 Verlet Algorithm	25

3. NUMERICAL IMPLEMENTATIONS AND SIMULATION RESULTS	27
3.1 Flow-chart of MD-based Simulation.....	27
3.2 Measurement of Aggregation Degree	34
3.2.1 Average Nearest Neighbour Distance Analysis (ANN).....	34
3.2.2 Nearest Neighbour Distance (NND).....	37
3.3 External factors	40
3.4 Irregular Boundary	44
4. SUMMARY AND FUTURE WORK	46
REFERENCES	49
VITA.....	52

LIST OF FIGURES

1	Alignment movement (a) movement of aggregation carp (b) alignment style	18
2	Interaction zones between neighboring carp.....	20
3	Comparison of energy (a) inter-carp potential energy (b) Lennard-Jones potential energy.....	21
4	Comparison of force (a) inter-carp force (b) Lennard-Jones force.....	22
5	Interaction between neighbouring carp.....	23
6	Ψ_{ij} value with variant β_{max}	24
7	Expected aggregation of carp (a) initial status; (b) after aggregation.....	26
8	Flowchart of the MD-based Simulation of Carp Aggregation.....	28
9	Snapshots about the simulation of carp aggregation (n=20) (a) Initial status (b) Snapshot at time step of 500 (c) Snapshot at time step of 1000 (d) Snapshot at time step of 1500	29
10	Snapshots about the simulation of carp aggregation (n=50) (a) Initial status (b) Snapshot at time step of 500 (c) Snapshot at time step of 1000 (d) Snapshot at time step of 1500	30
11	Snapshots about the simulation of carp aggregation (n=80) from time step 0 to 1500 (a) Initial status. (b) Snapshot at time step of 500 (c) Snapshot at time step of 1000 (d) Snapshot at time step of 1500.....	31
12	Snapshots about the simulation of carp aggregation (n=80) from time step 2000 to 3500 (e) Snapshot at time step of 2000 (f) Snapshot at time step of 2500 (g) Snapshot at time step of 3000 (h) Snapshot at time step of 3500	32
13	Plot of Average Nearest Neighbour Distance (ANN) and related snapshots about the simulation of carp aggregation (n=50) (1) ANN vs. time: within 3000	

time steps (2) Snapshot of carp aggregation status at a (3) Snapshot of carp aggregation status at b.....	36
14 Plot of Average NND of single time step and related snapshots about the simulation of carp aggregation with Temperature Mode On (n=50) (1) Average NND single time step vs. time: within 20000 time steps (2) Snapshot of carp aggregation status at a (3) Snapshot of carp aggregation status at b.....	38
15 Plot of top Average NND of single time step and related snapshots about the simulation of carp aggregation with Temperature Mode On (n=50) (1) top Average NND single time step vs. time: within 20000 time steps (2) Snapshot of carp aggregation status at a (3) snapshot of carp aggregation status at b.....	39
16 NND vs. Temperature (1) Experiment Data from simulation results (n=50) within 20000 time steps (2) Real observed data	42
17 Snapshots about the simulation of carp aggregation with Temperature Mode On/OFF (n=50/Time step=3000) (1) Aggregation status with Temperature Mode OFF (2) Aggregation status with Temperature Mode ON	43
18 Snapshots about the simulation of carp aggregation with IrgBMode On (n=50) (a) Initial status. (b) Snapshot at time step of 5000 (c) Snapshot at time step of 10000. (d) Snapshot at time step of 15000	45

LIST OF ABBREVIATIONS

AIS, Aquatic invasive species

CAWS, Chicago Area Waterway System

ACRCC, Asian Carp Regional Coordinating Committee

CSSC, Chicago Sanitary and Ship Canal

GLC, Great Lakes Commission

GLFC, Great Lakes Fisheries Commission

MD, Molecular Dynamics

ANN, Average Nearest Neighbor Distance ratio

NND, Nearest Neighbor Distance

LIST OF SYMBOLS

m , Mass

X , Coordinates

U , Potential energy

F , Force derived from potential energy

r , Distance vector between two carp

$\|r\|$, Distance between two carp

R_s , Radius of repulsion zone

R_h , Radius of parallel zone

R_k , Radius of attraction zone

σ , Constant coefficient for van der Waals forces

ε , Constant coefficient for van der Waals forces

β_{\max} , Maximal perceptible angle

β , The angle between individual carp velocity and vector of distance between two carp

Ψ , Angle dependent scaling function

μ , Constant coefficient for drag force

v , Individual carp velocity

v_{crit} , The threshold maximum velocity that a carp can obtain

CHAPTER 1

INTRODUCTION

1.1 Overview

Asian carp which dramatically increase in numbers and cause devastating effects draw great attention from society. As Asian carp are already well established throughout the Mississippi River Basin, their possible migration to the Great Lakes through the Chicago Area Waterway System (CAWS), Wabash River, Grand Calumet River, and other potential pathways demand proper actions to decrease the spread of Asian carp and prevent possible expansion (2013 Asian Carp Regional Coordinating Committee, 2013; 2014 Asian Carp Regional Coordinating Committee, 2014).

The Great Lakes, a series of interconnected freshwater lakes located in North America, consisting of Lakes Superior, Michigan, Huron, Erie, and Ontario. It is the largest group of freshwater lakes on Earth, containing 21% of the world's surface fresh water by volume. The Great Lakes cover more than 94,000 square miles and are an invaluable source of fishing. The Great Lakes are home to many important species of food and sport fish such as whitefish, bloater chubs, yellow perch, trout and walleye. However, the variety and quantity of fish has been undergoing great changes due to the introduction of Aquatic Invasive Species (AIS). More than 180 non-native species have been introduced into the Great Lakes since the beginning of the 19th century. Some of

these species, causing ecological or economic damage or threatening human health, have become “invasive” (Stein, Flack, Benton, & Conservancy, 1996). These invasive species can devastate native communities and cause great economic damage to the Great Lakes’ commercial, sport, and tribal fisheries. Native species especially the endangered species are considered at risk primarily because of predation or competition with exotic species. Introduction of Asian carp to the region could further stress these organisms and perhaps lead to their extinction.

Due to the potential ecological and economic damage caused by Asian carp infestation, Asian carp is considered one of the most serious invasive species threats facing the Great Lakes today. The alarm of Asian carp invasion into the Great Lakes leads state, local, and federal agencies to take pre-emptive actions.

1.2 Asian Carp

In North America, Asian carp usually refers to bighead carp (*Hypophthalmichthys nobilis*), silver carp (*Hypophthalmichthys molitrix*), black carp (*Mylopharyngodon piceus*), and grass carp (*Ctenopharyngodon idella*) (Asian Carp Regional Coordinating Committee, 2016). They all are members of the family Cyprinidae. Silver carp and bighead carp are singled out because they pose a significant threat to the waters they invade and require rapid response. Bighead and silver carp species were originally imported into the Mississippi River watershed 30 to 40 years ago. Southern United States aquaculture and wastewater treatment facilities use these carp to improve water quality (keep retention ponds clean) and to serve the food fish industry.

There are many potential ways by which Asian carp may have escaped, including inadvertent releases, overland flooding events and intentional releases. No matter how they escaped, Asian carp have gradually established breeding populations in the Mississippi Basin and become undesirable pest species. Since their introduction to Arkansas sewage lagoons and aquaculture ponds in the early 1970s, Silver carp have spread to 23 surrounding states and as far north as South Dakota and Minnesota (Buck, Upton, Stern, & Nicols, 2010).

Asian carp are poised to invade the Great Lakes and might pose a significant threat to the ecological and economic value of the neighboring Great Lakes. During 2002, they were detected in the upper Illinois River just 60 miles from Lake Michigan. In 2009, a bighead carp was retrieved considerably closer, within the Lockport Pool of the Chicago Sanitary and Ship Canal (CSSC), 43 miles from Lake Michigan. In June 2010, through enhanced monitoring operations, one bighead carp was found in Lake Calumet, 5 miles from Lake Michigan. During 2012, monitoring of the Asian carp population in the Illinois River revealed that spawning activity of Asian carp was approximately 152 miles from Lake Michigan, and a moderate to abundant numbers of adults was detected approximately 62 miles from Lake Michigan. Chicago seems to be Asian carp's final stop before their entering into Great Lakes (2013 Asian Carp Regional Coordinating Committee, 2013; 2014 Asian Carp Regional Coordinating Committee, 2014; 2015 Asian Carp Regional Coordinating Committee, 2015).

1.2.1 Diet and Life History

Asian carp, also known as bigheaded carp, can weigh up to 100 pounds or more, although such sizes are rare. Bighead carp can live over 20 years, grow over 5 feet in length, and commonly weigh up to 40 pounds. Silver carp are generally smaller than bighead carp, weighing up to 20 pounds. They share similar feeding and spawning habits (Koel, Irons, & Ratcliff, 2000).

Asian carp are planktivorous, eating predominantly phytoplankton and zooplankton, but can be opportunistic and consume a variety of food sources. Gut analysis of Asian carps in the Missouri River revealed that these carps primarily eat detritus, which may indicate diversified diets and therefore an ability to survive in a variety of environments. Asian carp feed on plankton at the base of the food web. Most native fishes eat zooplankton during part of their life cycle, and some rely directly on plankton throughout their lives. The dietary overlap may allow Asian carps to out-compete Great Lakes native fishes.

Adult Asian carps usually select habitats with low water velocity and depths more than 2 meters. They are active in cold water; increased activity and feeding began when the water temperature rises above 2–4 °C (36–39 °F). Maturity is reached between 2 and 7 years of age, depending on the climate and population levels (Kolar et al., 2007). Asian carp lay their eggs in flowing water, and their eggs and larvae drift in the current. Once they start to swim, Asian carp begin to move to low velocity tributaries. Early life stages of Asian carp typically inhabit warm, productive, protected, backwater and wetland areas (Amberg, 2012).

Silver carp are often referred to as “flying fish.” When disturbed by boat motors and

startled, these fish will jump from the water, injuring boaters, anglers, and other recreational users or damaging equipment. Sometimes schools of silver carp will jump simultaneously. Unlike the silver carp, the bighead carp does not jump in response to boat traffic.

Asian carp exhibit strong schooling behavior. Carp live in small, dispersed groups during the summer time. However, large aggregations in ice-covered lakes of the North American Midwest and Eastern Europe have been reported (Bajer, Chizinski, & Sorensen, 2011). In laboratory studies, they show substantial preference for the chemical cues of the school (2015 Asian Carp Regional Coordinating Committee, 2015). Such a stimulus may be useful as a lure to capture bigheaded carps in the wild.

1.3 Lessons and Impacts

Increasing data indicates that an invasion into the Great Lakes by Asian carp could be financially, ecologically, biologically, and socially devastating. These categories of impact are interconnected, all significantly affecting one another.

1.3.1 Potential Risk to the Great Lakes Basin

The potential impact of Asian carp on the Great Lakes' sport and commercial fishing industry can be foreseen now in the Mississippi River Basin where in a few short years following Asian carp introduction, many commercial fishing locations have been abandoned, as native fish have been significantly impacted by Asian carp. Because Asian

carp populations could reach self-sustaining levels near the confluence of the Lake Michigan tributaries and canals in the Chicago vicinity, it is highly possible that Asian carp would move to new areas, seeking suitable habitat and resources through density-dependent dispersal. These types of water bodies that can provide good environment condition for Asian carp to achieve an established population are found within Lake Michigan and throughout the entire Great Lakes Basin. According to current data, Asian carp species are dominating the Mississippi River Basin and reaching to the very edge of the Great Lakes.

1.3.2 Ecological and Biological Risk

Assessments indicate that the Great Lakes Basin's climate cater to the growth of Asian carp, because the climate in basin is similar to their native climate range. Bighead carp requires mean annual air temperatures that range between -2 °C and 22 °C while silver carp requires a range between -6°C and 24°C. Such kind of temperature span could be found in much of the United States and Canada, including the Great Lakes (Herborg, Mandrak, Cudmore, & MacIsaac, 2007).

To successfully complete their life cycle, Asian carp need access to a suitable habitat for spawning of adults, for development and hatching of eggs, for recruitment of larvae and early juveniles, and for growth and survival of sub-adults and adults. The Great Lakes and inland bodies of water provide a diverse array of habitat types and would therefore likely provide the necessary physical habitat components for all life stages of Asian carp.

Taking advantage of great conditions like water temperature, food abundance, slow-moving wetland regions, expansive area for migration in the Great Lakes and their tributaries and estuaries, Asian carp that lack of natural predators can easily expand in Great Lakes. During the same time, Asian carp would likely out-compete native fish for food and space. Due to their dietary habits and high fecundity, Asian carp could greatly change the energy flow in the local ecosystems, resulting in changes in the native habitats and populations of these ecosystems. Thus comes our concern-- the invasive issue. The invasive sea lamprey, which has changed the Great Lakes ecosystem forever, demonstrates the profound impact one invasive species can exert on an ecosystem. The sea lamprey invasion also indicates that invasive species are nearly impossible to eradicate. Mandrak and Cudmore pointed out that the consequences of establishment of grass and silver carp on the genetics of native species would be certain and significant (Mandrak & Secretariat, 2004). Following introduction of Asian carp into the Great Lakes basin, controlling their spread throughout these areas could be nearly impossible. These species could significantly impact local ecosystems.

1.3.3 Financial Risk

An Asian carp invasion can not only cause significant, permanent damage to the ecological health of a region, but can also affect the economy of related area. It is known from experience that dealing with invasive species after their establishment is difficult and expensive. For example, over \$300 million was spent by the Great Lakes Fisheries Commission (GLFC) since 1956 to control sea lampreys, an invasive species to the Great

Lakes. However, this expenditure is considered a fraction of the billions of dollars in revenue lost because of the sea lamprey's direct role in decline of lake trout, a native keystone species, by a staggering 99 percent (2015 Asian Carp Regional Coordinating Committee, 2015).

Fishing in the Great Lakes is an industry estimated to generate billions of dollars of revenue. An invasion of Asian carp to the Great Lakes could be detrimental to the fishing industry and those financial assets. The potential financial risk to fishing alone indicates the significance of an Asian carp invasion to the Great Lakes region.

1.3.4 Social Risk

The social implications of an Asian carp invasion of the Great lakes range from outcompeting, and thus eradicating, native sport populations to physical harm to people. The Great Lakes Commission (GLC) estimates that nearly 1 million boats and personal watercraft operate on the lakes, thereby placing more than a million people in potential contact with the silver carp, a projectile fish. The hazards these projectile fish pose to those boating, jetskiing, and waterskiing on the Illinois River system would be compounded on the Great Lakes because of a significantly larger boating population, thus posing a larger health and safety issue.

The social risk that Asian carp represent to the Great Lakes is directly relevant to the financial risk as well. If Asian carp do make their way into the Great Lakes, recreational activities could be significantly affected, directly impacting revenue based on those activities.

Other financial and social costs might also be associated with actions needed to stop Asian carp from entering the Great Lakes. About seven million tons of cargo and more than 19,000 recreational boats pass through the O'Brien Lock each year, not to mention additional cargo, ferry, and pleasure boats using the Chicago Lock. In 2010, 11,699 lockages and 36,334 vessels passed through the Chicago Lock—volume second only to the Hiram M Chittenden Locks in Seattle, Washington. To stop the invading of Asian carp, permanent closure to the Chicago area locks would be one extreme strategy. This strategy would greatly affect commerce and recreational use of Lake Michigan and the CAWS (2015 Asian Carp Regional Coordinating Committee, 2015).

1.4 Control Strategies

The battle against Asian carp is not carried out recently. In 2009 and 2010, the Great Lakes States invested over \$26.7 million in prevention and control of aquatic invasive species—of which almost \$900,000 was committed to Asian carp control efforts. Since 2011, an unprecedented and comprehensive set of actions to prevent introduction and establishment of Asian carp populations in the Great Lakes has been carried out by ACRCC, with support from federal, state, provincial, and local agencies, as well as from private stakeholders and citizens. The funding used in Asian carp prevention, management, and control programs has increased to \$61,055,036 in 2014 (2015 Asian Carp Regional Coordinating Committee, 2015). The ACRCC seeks development of an effective and fiscally sustainable Asian carp prevention and control program throughout the Great Lakes Basin. It is undoubted that preventing establishment of a self-sustaining

Asian carp population requires a comprehensive approach, which cannot rely on one single strategy. Like other invasive species, Asian carp follows steps common to the invasion of many species: introduction, establishment and spread. It would be premium to stop the invasion in the very beginning, so it is reasonable that the greatest efforts are taken in prevention and in development of prevention technologies, followed by efforts to stop establishment, and then by developing technologies to minimize spread of Asian carp in the CAWS and Great Lakes (if this proves ultimately possible) (Lodge et al., 2006).

Each stage requires different management strategies. However, Asian carp removal action plays a special role in those management strategies. As a preventing and control method, it can be used to reduce current Asian carp populations in infested waterways, potentially lowering the risk of a Great Lakes invasion. If further developed and applied properly, it can effectively eliminate Asian carp species or prevent their movement while minimizing damage to native biota. The existed data indicate the promising application future for the removal actions.

For example, in order to address the impact of the Asian carp that already exist within the Illinois River below the electric barrier system, a program of Commercial Harvesting and Removal was established. In 2010, contract commercial fishermen harvested 60 tons of Asian carp from the Illinois River. In 2011, over 23,000 bighead carp and 17,000 silver carp were removed in 61 days of fishing. Combined, over 351.7 tons of Asian carp were removed from the river. In 2012, over 284 tons of Asian carp was removed from the river (2015 Asian Carp Regional Coordinating Committee, 2015). The fact that catch rates across the areas fished that declined on a year-to-year basis indicate consistent

removal achieved great results. It appears that Asian carp populations are not expanding within the harvest area and that Asian carp are not moving farther upstream toward the CAWS and Lake Michigan.

Future commercial harvesting efforts will carry on. According to 2016 Asian Carp Action Plan (new name for the Asian carp control strategy framework), contract fishing to reduce the numbers of Silver and Bighead Carp in the upper Illinois and lower Des Plaines rivers downstream of the electric barrier will be increased by 50 percent (Asian Carp Regional Coordinating Committee, 2016). Based on current trends, catch rates and overall removal rates of Asian carp are expected to continue to decrease with time because of harvest and other control measures. Research is currently underway to develop more effective harvesting methods that are in demand. Other than the study and analysis of net-avoidance behavior in Asian carp and Asian carp reactions to different types of netting and harvesting techniques, as well as more advanced fishing gear, Bajer's work inspired efforts to increase the fishing efficiency taking advantage of aggregation behaviors of Asian carp (Bajer et al., 2011).

Bajer's study demonstrated that common carp inhabiting Midwestern lakes form tight winter-time aggregations that can be precisely tracked and removed using small numbers of radio-tagged Judas fish. In this technique, a few individuals are captured, radio-tagged and then followed as they relocate (and inadvertently betray) the groups in which they normally live and which can then be targeted and removed. Conventional commercial seining guided by Judas fish achieved high removal rates (52–94%), suggesting that fishing with the Judas technique could be very useful in carp control (Bajer et al., 2011). It is especially promising that carp will move between lakes and aggregate at single

locations, implying removing the majority of carp in the entire systems of lakes might be possible.

CHAPTER 2

MODEL ESTABLISHMENT

To provide further useful information for controlling the populations of Asian carps, we need to accurately understand the collective behaviour of Asian carps such as aggregation. This paper is dedicated to proposing a molecular-dynamics based mathematics model to formulate the aggregation of Asian carps with certain initial conditions which might provide insightful predication of carp future movement.

2.1 Background

Due to its theoretical significance and practical applications potential, the study of animal aggregation draws great attention from scientists. Aggregation as a group formation is influenced by external factors and internal factors, which are social forces that act among individuals. More focuses are placed on the internal factors that lead to group formation. A large number of mathematical models have been derived for the purpose of better understanding animal aggregations. Most of these models are in two spatial dimensions, and include all three types of social interactions that alter the position of an individual: attraction, repulsion, and alignment. In most cases, structural features of the group (e.g., geometry of the group, degree of polarization, etc.) are emphasized, and

simulations achieve very close agreement with the swarm, torus, dynamic parallel groups, and highly parallel groups that are observed in nature.

Reynolds in his study on birds in a flock, proposed a distributed behavior model, an alternative to scripting the paths of each bird individually. The simulated flock is considered as a particle system, with the simulated birds being the particles. Each simulated bird navigates according to its local perception of the dynamic environment and behaves according to the laws of simulated physics (Reynolds, 1987). This type of individual-based computer simulation is considered a very useful analytical tool to study groups like fish schools and bird flocks, so this initial model was further used by followers.

Later on, Vicsek et al. also adopted Reynolds's pro-type model and made particles in their model driven with a constant absolute velocity. At each time step these particles assume the average direction of the motion of the particles in their neighborhood with some random perturbation added (Czirók, Stanley, & Vicsek, 1997; Vicsek, Czirók, Ben-Jacob, Cohen, & Shochet, 1995). Vicsek's model further developed into three dimensions to observe collective motion of flocks. Their later simulation takes into consideration biological reality and simulates the behavior of individuals as resulting from local repulsion, alignment and attractive tendencies based upon the position and orientation of individuals relative to one another (Czirók, Vicsek, & Vicsek, 1999). However, this model does not include any possible environmental factors that might influence group behavior. Similarly, Eftimie et al. started with the hypothesis that each individual interacts with its neighbors via three social forces: attraction, repulsion, and alignment. Each of these forces has a different interaction range. An individual changes direction to

approach other individuals if they are within its attraction range, or to avoid collision if they are within its repulsion range. Moreover, an individual turns to match its orientation to its neighbors' direction of movement (i.e., to align) if they are within its alignment range. All three social interactions influence the turning rates for the individuals that were initially moving to the right (left) and then turn to the left (right) (Eftimie, de Vries, Lewis, & Lutscher, 2007). However, this model focuses more on achieving different movement patterns merely by using inter-particle communication like the former model. Beside, only one spatial dimension is investigated. In nature, the majority of biological aggregations are in two or three dimensions, such as groups of migrating bacteria, colonies of ants, schools of fish or flocks of birds.

Hemelrijk et al. create a three-dimensional model. Each individual is characterized by its position, its scalar speed and its orientation in space. Its orientation is indicated by its forward direction, e_x , its sideward direction, e_y and its upward direction, e_z , which it changes by rotations around these three principal axes, e_x , e_y and e_z (roll, pitch and head), as in the model by Reynolds. In the model, individuals also follow three main rules: they avoid others that are close by, they align to others up to an intermediate distance and they are attracted to individuals further away. Hemelrijk et al. made improvement. First, they gave individuals control over their speed in a more natural way instead of fixing the speed at a certain value with random error. Individuals move at a cruise speed towards which they return after speeding up to catch up with others or slowing down to avoid collision. Second, individuals are unlikely to perceive those that are hidden behind others thus to avoid perception includes all group members. In this way, individual range of perception would be more flexible. It is reduced when the local density of individuals is

high, and it increases, when the density is low. Third, the model can be used to create schools of a relatively large range of sizes (10-2000) (Hemelrijk & Hildenbrandt, 2008). Despite the model's effort to minimize difference between simulation results and real fish aggregation, the model still place major attention on interaction between neighbors without any consideration of external effects.

2.2 Model establishment

Our proposed model assumes each individual carp as an independent unit which means a carp has its own behavior and interacts with other carp or the environment. The aggregation behavior (school, mill, and swarm) results from the collective behavior of individual carp. It is common to consider the following factors: attraction toward other individuals, repulsion from others, and the tendency to align with neighbors (i.e., to adjust the movement direction to that of neighbors). Each of these forces acts over a certain spatial scale or within a certain range of influence. We chose to follow the most widespread model, where fish interactions encompass a short-range repulsion zone, middle-range alignment zone (horizontal zone) and far-range attraction zone (Czirók et al., 1997; Czirók et al., 1999; Eftimie et al., 2007; Hemelrijk & Hildenbrandt, 2008; Reynolds, 1987; Vicsek et al., 1995). However, to imitate the neighboring interaction, the analogy of van der Waals forces is used in this work. In convention, the new swimming direction and velocity depend on the positions, orientations and velocities of neighboring fishes. The different influences of the neighboring fishes are averaged. For example, the new velocity of a fish is calculated by averaging the velocities of a certain number of

neighbors. The new direction is determined by the influence of each neighbor fish, using a potential turning angle for the influenced fish. The average of these turning angles is used as the actual turning angle of the influenced fish. By adopting an individual-based model, we hope that this model will provide more space to include biological features that are crucial for carp aggregation and help spot certain behavioral traits of carp that might lead to a collective phenomenon. In our current simulation, the motivations of fish aggregation, such as foraging advantages, reproductive advantages, predator avoidance, or hydrodynamic efficiency, are disclosed. Other than the aim to achieve group behavior patterns that can be observed, the model is also capable of incorporating external factors which will be implemented by changing the inter-carp forces.

The mathematical model to be addressed in this work is derived from the following primitive assumptions:

1. The aggregation of carp is completely a random and spontaneous behavior. In other words, carp aggregation is not a social behavior but a result of instinctive activity of individual carp.
2. Aggregation of carp is a gradual process, which is originated from the collision of two individual carp or two schools of carp.
3. Collision indicates that two carp or two schools of carp approach each other within a perceptible distance.
4. The aggregated carp are coordinated via neighboring interaction, which is defined by the analogy of van der Waals forces in this work.

2.2.1 Interaction between neighbouring carp

As illustrated in Figures 1(a) and (b), carp in aggregation move in “alignment style”. Aligned movement of a carp school is the collective effect of the pair-wise interaction of neighbouring carp.

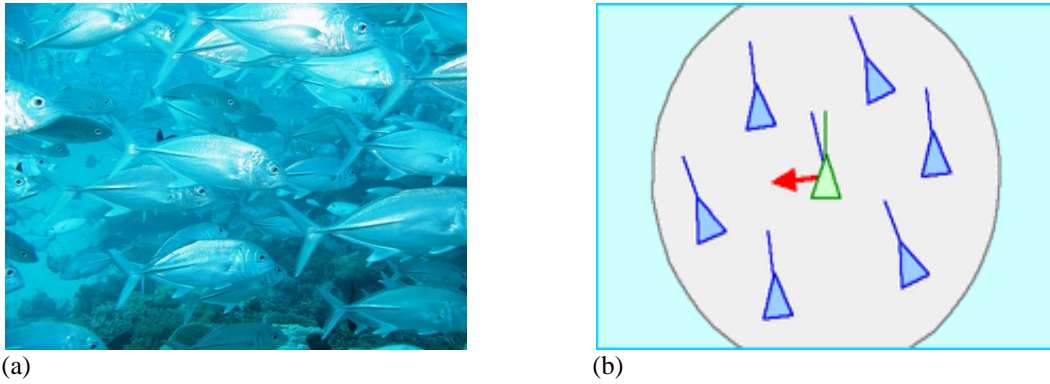


Figure 1 Alignment movement (a) movement of aggregated carp (b) alignment style

Carp aggregation consists of the numerical solution of the Newton’s second law, which can be written as

$$m_i \frac{d^2 X_i}{dt^2} = F_i, \quad F_i = -\frac{\partial}{\partial X_i} U.$$

where m_i and X_i indicate the mass and coordinates of i -th carp respectively. The force F_i indicates the influence from other carp and the external environment; it is derived from the global potential energy U . The global potential energy is divided into pair-wise potential energy (or two-body energy) and can be expressed as

$$U = \sum_i \sum_{j>i} U_{ij}.$$

For the sake of simplicity, the externally applied potential energy and three-body (or higher-order) interaction are ignored in this section.

2.2.2 Interaction of Carp without Blind-Zone

In this work, the pair-wise interaction U_{ij} is defined using modified van der Waals forces, where the corresponding potential function U_{ij} between carp-i and carp-j is defined by the following formula:

$$U_{ij} = \begin{cases} 4\varepsilon \left[\left(\frac{\sigma}{\|r_{ij}\|} \right)^{12} - \left(\frac{\sigma}{\|r_{ij}\|} \right)^6 \right] & (\|r_{ij}\| < R_s) \\ 4\varepsilon \left[\left(\frac{\sigma}{R_s} \right)^{12} - \left(\frac{\sigma}{R_s} \right)^6 \right] & (R_s \leq \|r_{ij}\| \leq R_h) \\ 4\varepsilon \left[\left(\frac{\sigma}{\|r_{ij}\| - R_h + R_s} \right)^{12} - \left(\frac{\sigma}{\|r_{ij}\| - R_h + R_s} \right)^6 \right] & (R_h < \|r_{ij}\| < R_k) \end{cases}$$

where $r_{ij} = X_i - X_j$ and $\sigma = \frac{R_s}{\sqrt[6]{2}}$. R_s , R_h and R_k are illustrated in the formula in Figure

2. $\|r_{ij}\|$ indicates the distance between two neighboring carp. σ and ε are constant coefficients for van der Waals forces. It should be noted that the moving orientation, water flow velocity and blind zone are not considered in the formulation of the formula.

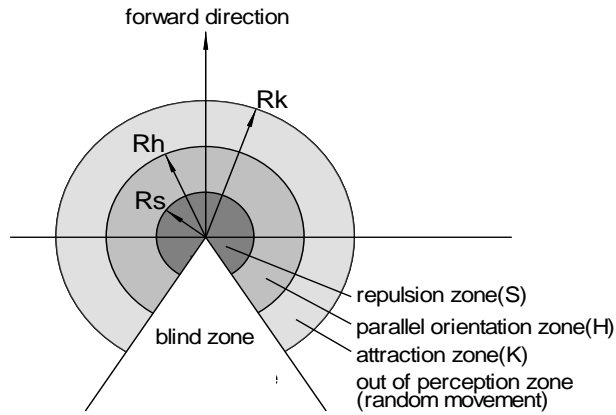


Figure 2 Interaction zones between neighboring carp

The potential energy incurred by the pair-wise interaction between two neighboring carp is shown in Figure 3(a). As a comparison, the Lennard-Jones potential energy is also shown in Figure 3(b). It can be observed that, inter-carp potential energy has a stable zone (or parallel zone), within which the inter-carp potential energy is basically constant so that the neighboring carp can cruise without influencing each other. In reality, the repulsion zone, parallel orientation zone and perception zone are not constant but dependent on many factors such as velocity, temperature and light condition, etc.

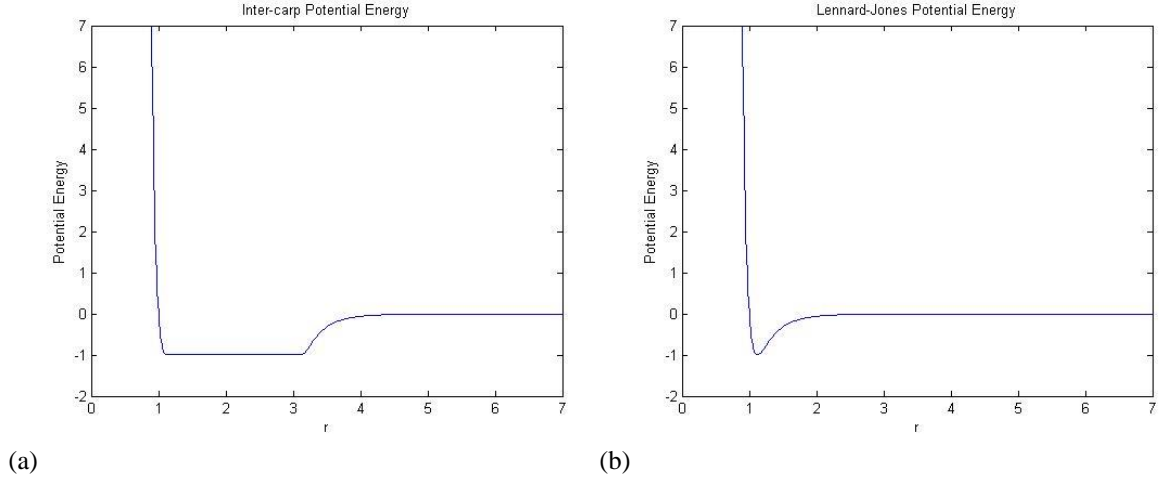


Figure 3 Comparison of energy (a) inter-carp potential energy (b) Lennard-Jones potential energy

Derived from the potential energy, the interaction force can be defined as follows:

$$f_{ij} = -\frac{\partial U_{ij}}{\partial \|r_{ij}\|}$$

$$= \begin{cases} -24 \frac{\varepsilon}{\sigma} \left[2 \left(\frac{\sigma}{\|r_{ij}\|} \right)^{13} - \left(\frac{\sigma}{\|r_{ij}\|} \right)^7 \right] & (\|r_{ij}\| < R_s) \\ 0 & (R_s \leq \|r_{ij}\| \leq R_h) \\ -24 \frac{\varepsilon}{\sigma} \left[2 \left(\frac{\sigma}{\|r_{ij}\| - R_h + R_s} \right)^{13} - \left(\frac{\sigma}{\|r_{ij}\| - R_h + R_s} \right)^7 \right] & (R_h < \|r_{ij}\| < R_k) \end{cases}$$

Figure 4(a) shows the inter-carp force field. As a comparison, the force field derived from Lennard-Jones potential energy is given in Figure 4(b).

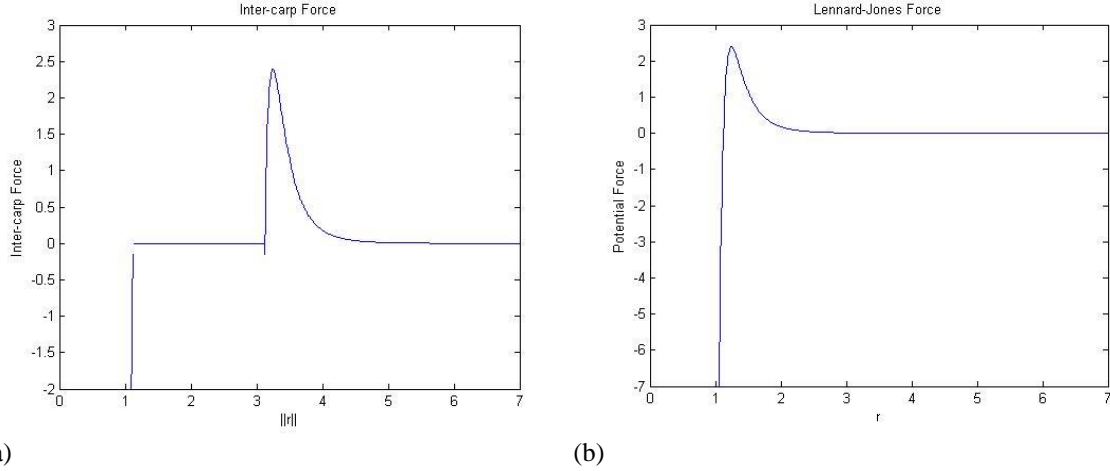


Figure 4 Comparison of force (a) inter-carp force (b) Lennard-Jones force

2.2.3 Interaction of Carp with Blind-Zone

This subsection will discuss the pair-wise potential energy and force between carp with the blind-zone. As illustrated in the Figure 5, v_i is the velocity of i -th carp. β_{\max} is the maximal perceptible angle, obviously $0 \leq \beta_{\max} \leq \pi$. β_{ij} indicates the angle between v_i and r_{ij} , and is defined by the following formula:

$$\beta_{ij} = \arccos\left(\frac{v_i \circ r_{ij}}{\|v_i\| \|r_{ij}\|}\right)$$

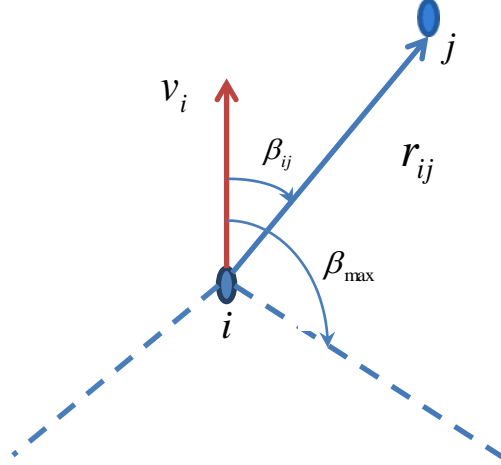


Figure 5 Interaction between neighbouring carp

Given the blind-angle β_{\max} , the inter-carp potential is defined as:

$$U_{ij}^* = \Psi_{ij} U_{ij}$$

where

$$\Psi_{ij} = \Psi(\beta_{ij}) = \frac{\sqrt{\pi}}{\beta_{\max} \sqrt{2}} e^{\frac{-\pi^2 \beta_{ij}^2}{2\beta_{\max}^2}}.$$

As a consequence, the inter-carp interaction force is determined by the following formula:

$$F_{ij}^* = \frac{\partial}{\partial \|r_{ij}\|} U_{ij}^* = \Psi_{ij} F_{ij},$$

where F_{ij} is defined in the former equation as f_{ij} .

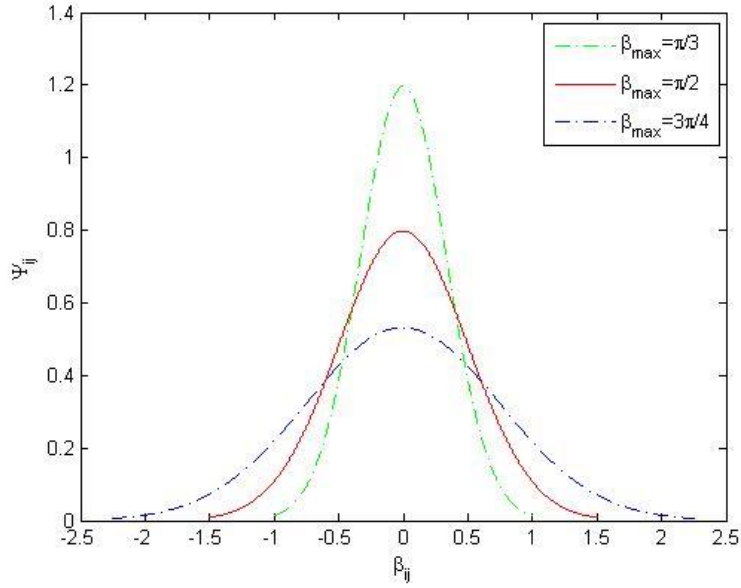


Figure 6 Ψ_{ij} value with variant β_{\max}

2.2.4 Higher-order Interaction

The former section only focused on the pair-wise interaction; however, the real situation will be more complicated as more than two carp will interact with each other. The model needs to handle more than pair-wise situations. It is highly possible that compound attraction forces from more than two neighboring carp will lead to a great acceleration to certain individual carp. In our initial model implementation, we found that carp will go through the parallel zone and hit each other and bounce back when more than two carp are involved in the interaction. To tackle this problem we investigate two strategies: scaling and the introduction of extra force. In scaling, when individual carp velocity is over specified maximum velocity, the velocity will be scaled down to its initial velocity. As to the latter strategy, the force which is positively related to carp

velocity is implemented. Thus one carp will undergo large “drag” if it accelerates to an extremely large velocity, and it will suffer relatively less from “drag” if its velocity is small. The formula we used for the drag can be expressed as follows:

$$F_d = \mu v (v > v_{crit})$$

where μ is constant coefficient for drag force, v is the individual carp velocity and v_{crit} is the threshold maximum velocity that a carp can obtain.

2.3 Verlet Algorithm

By introducing the momentum of carp, the trajectory status of carp (Figure 7) can be obtained using the following Verlet algorithm (S Fernandes, Liang, Sritharan, Wei, & Kandiah, 2010; Shane Fernandes & Liang, 2013):

$$\begin{cases} p_i(t + \frac{1}{2} \Delta t) = p_i(t) + \frac{1}{2} \Delta t F_i(t) \\ X_i(t + \frac{1}{2} \Delta t) = X_i(t) + \Delta t p_i / m_i \\ p_i(t + \Delta t) = p_i(t + \frac{1}{2} \Delta t) + \frac{1}{2} \Delta t F_i(t + \Delta t) \end{cases}$$

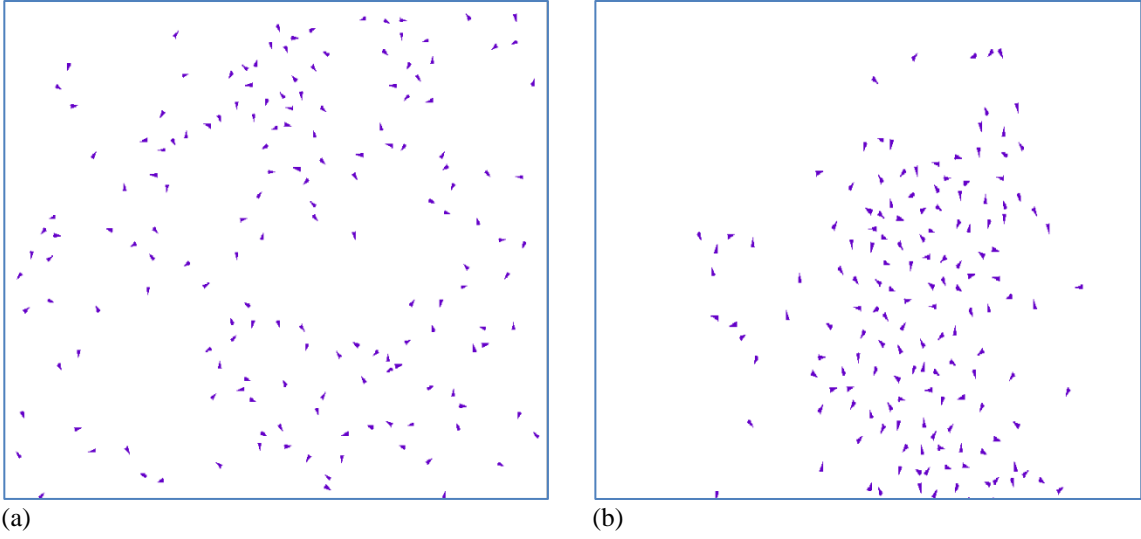


Figure 7 Expected aggregation of carp (a) initial status; (b) after aggregation

CHAPTER 3

NUMERICAL IMPLEMENTATIONS AND SIMULATION RESULTS

3.1 Flow-chart of MD-based Simulation

Figure 8 shows the flowchart of an MD-based simulation about the aggregation of carp. The phenomenon of carp aggregation is obtained by the simulation of our established model. As illustrated in Figures 9-12, each single carp fish is represented simply by a triangle-shaped particle. In the beginning of simulation, every carp randomly locates in the canvas and presents a random velocity. When the analogy of van der Waals force works, they start to get closer to or farther from each other and form a carp ensemble. This simulation imitates collective movements like swarm and school. In the following picture, we show the aggregation of “fish” with a maximum perceptible angle of $\beta_{\max} = \frac{2\pi}{3}$ in a 700 X 700 canvas. Fish that hit the wall are reflected and keep the same velocity. The size of fish groups are 20, 50 and 80 respectively. The radiuses of the repel zone R_s , parallel zone R_h and attraction zone R_k are respectively about 12, 28 and 48 times the length of fish. The constant coefficient σ is determined by R_s , while ε is adjusted according to the particular zone. In this case, we set $\varepsilon = 5e-3$ in the repel zone and $\varepsilon = 5e5$ in the attraction zone for a group size of 20 (Figure 9), $\varepsilon = 5e-2$ in the repel zone and $\varepsilon = 5e4$ in the attraction zone for a fish group size of 50 (Figure 10),

$\varepsilon = 5e-5$ in the repel zone and $\varepsilon = 5e4$ in the attraction zone for a group size of 80. The results that are captured for every 500 time steps ($dt = 1e-2$) are shown in Figures 9-11.

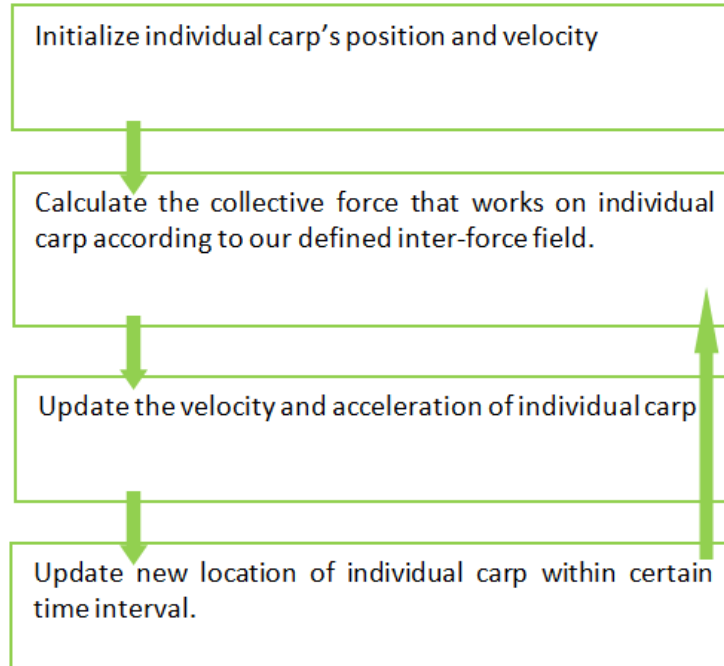


Figure 8 Flowchart of the MD-based Simulation of Carp Aggregation

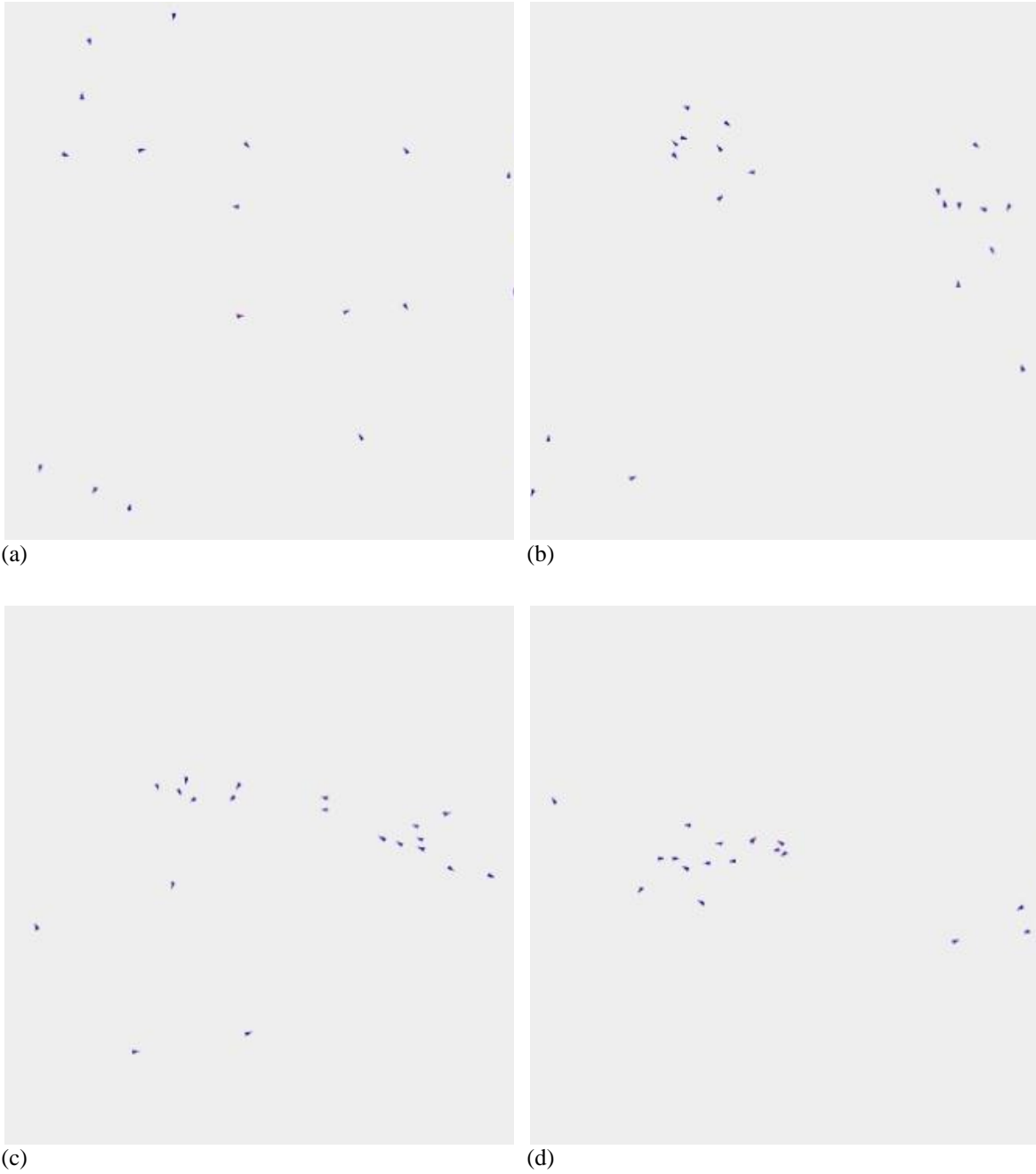


Figure 9 Snapshots about the simulation of carp aggregation ($n=20$) (a) Initial status (b) Snapshot at time step of 500 (c) Snapshot at time step of 1000 (d) Snapshot at time step of 1500

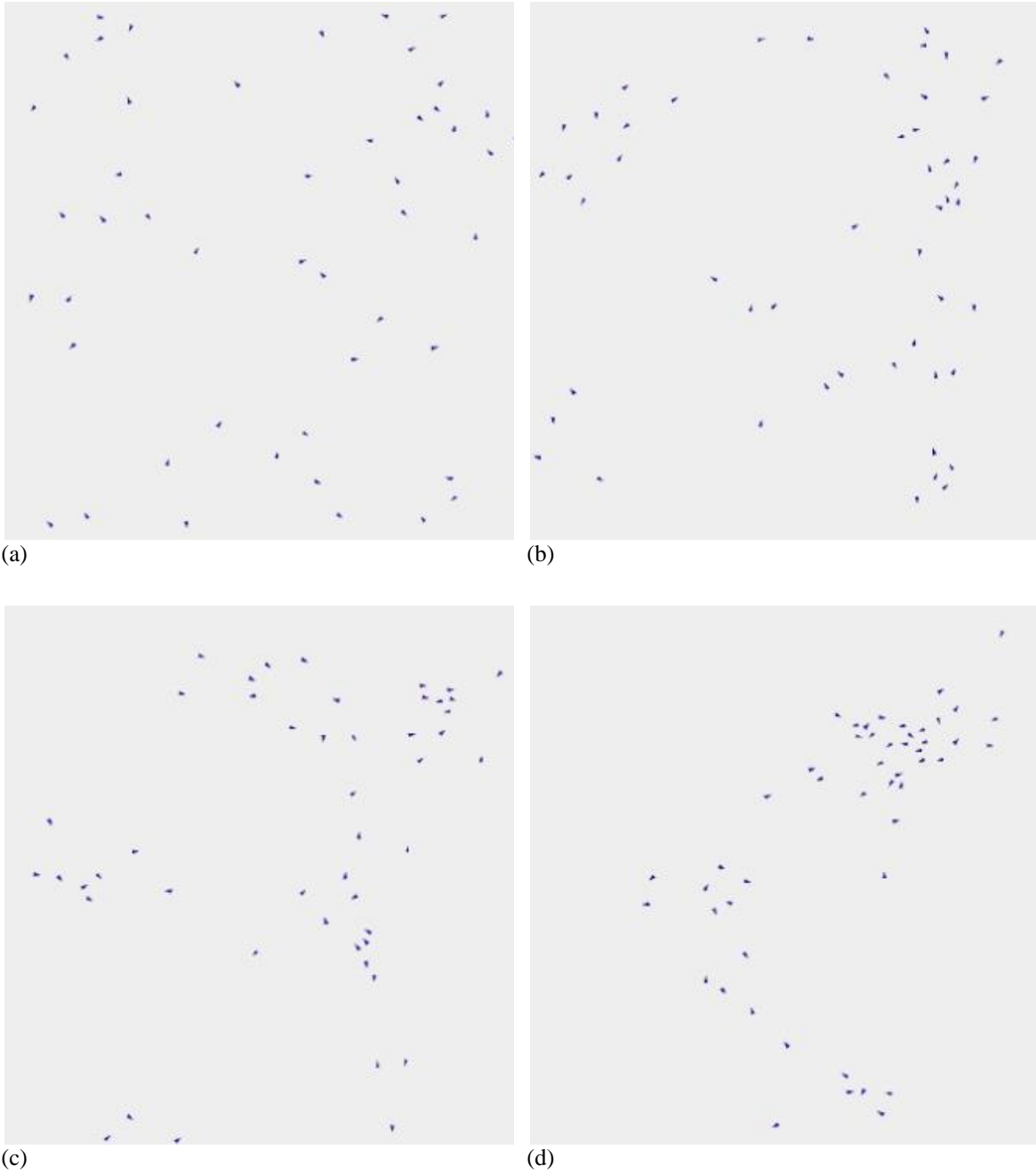


Figure 10 Snapshots about the simulation of carp aggregation ($n=50$) (a) Initial status (b) Snapshot at time step of 500 (c) Snapshot at time step of 1000 (d) Snapshot at time step of 1500

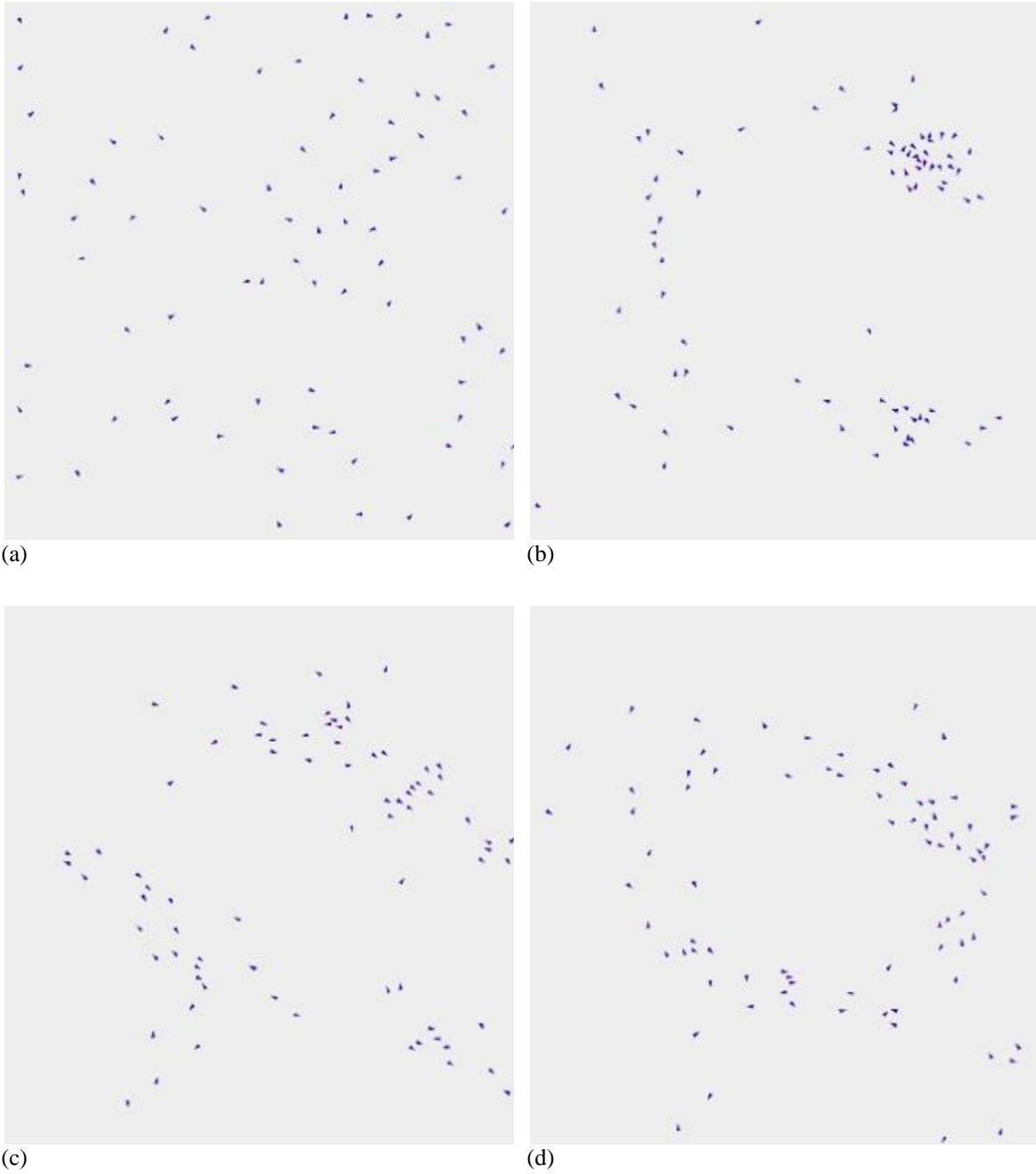


Figure 11 Snapshots about the simulation of carp aggregation ($n=80$) from time step 0 to 1500 (a) Initial status. (b) Snapshot at time step of 500 (c) Snapshot at time step of 1000 (d) Snapshot at time step of 1500

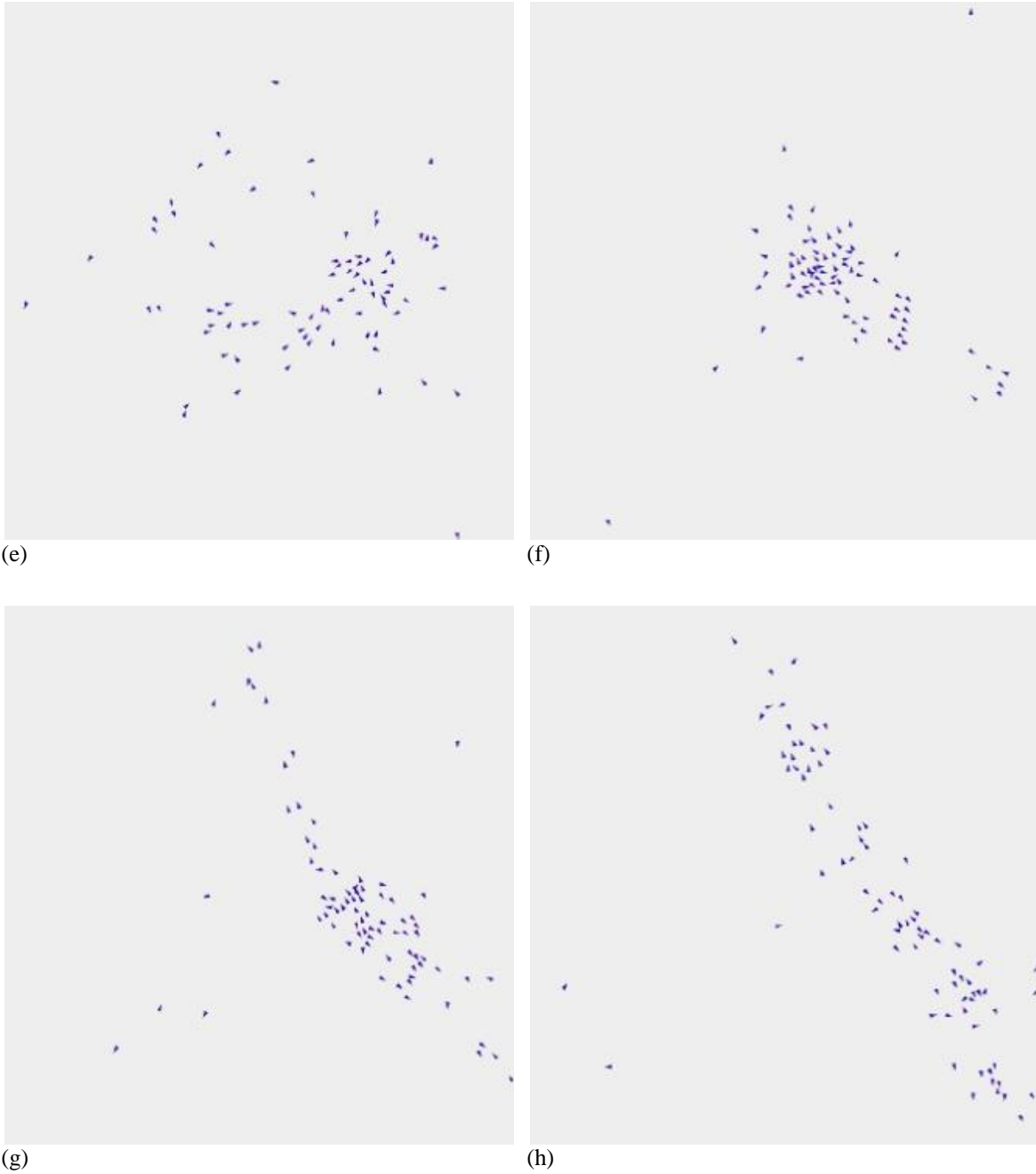


Figure 12 Snapshots about the simulation of carp aggregation ($n=80$) from time step 2000 to 3500 (e) Snapshot at time step of 2000 (f) Snapshot at time step of 2500 (g) Snapshot at time step of 3000 (h) Snapshot at time step of 3500

In Figures 9-11, the first picture in the first row of each figure shows the initial status of the carp, which is randomly and evenly located on the canvas (size of 20, 50 and 80 respectively). Due to the relatively lower density, fish groups of size 20 do not exhibit very obvious aggregation, but we can still tell smaller groups are able to follow each other. After starting simulation, we can tell from fish of size 50 and 80 that small groups are gradually formed and then combined to form larger groups. The collision of larger group achieves the formation of a swarm. As we take into account the blind zone in this model, the individual fish, which cannot perceive the existence of the aggregated fish behind them, start to move in separate directions. We can tell from Figures 11 and 12 that there are several groups of fish in different directions. Without the blind zone, a big group that once formed will not separate into a small group again. The results from our simulation are a contrast to the simulation results from Huth's model, in which the omission or addition of the blind zone does not change the results of simulations (Huth & Wissel, 1994).

The current model is able to characterize the aggregation of fish. However, to improve the accuracy, we need further investigation of other possible factors that might affect individual fish behaviour and therefore change the collective behaviour pattern. For example, we did not consider the function of the fish lateral line, which allows a fish to sense the region behind it in the current model. Besides, we should also weigh the role of the mass of individual fish, as the acceleration might differ greatly due to a change in mass.

3.2 Measurement of Aggregation Degree

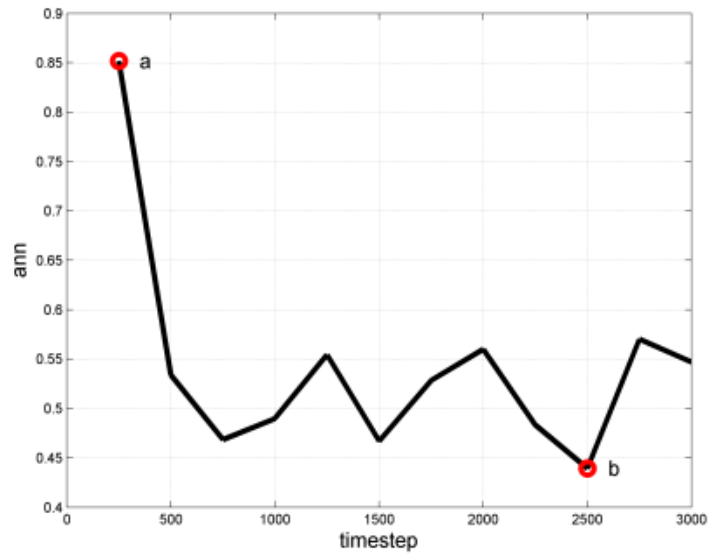
Aggregation, as a pattern of distribution of a population, is a feature that is extremely difficult to describe. We need to demonstrate that the carp is not randomly distributed; however, the degree of departure from random status is difficult to ascertain. In this case, we chose to use Nearest Neighbour Distance Analysis to give a quantitative analysis of the distribution of carp.

3.2.1 Average Nearest Neighbour Distance Analysis (ANN)

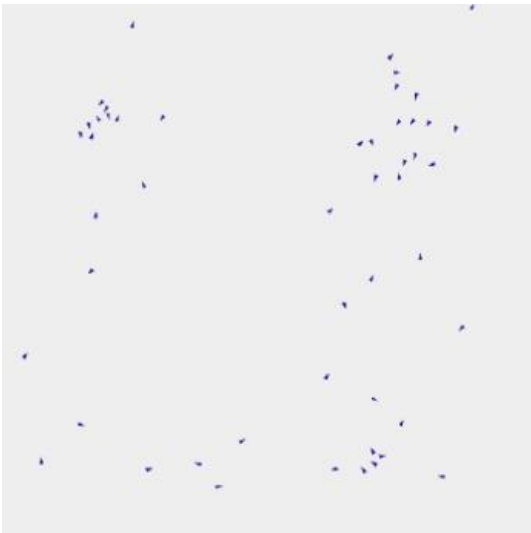
The Average Nearest Neighbour Distance (ANN) measures the distance between each featured centroid and its nearest neighbour's centroid location. It then averages all these nearest neighbour distances. If the average distance is less than the average for a hypothetical random distribution, the distribution of the features being analyzed is considered clustered. If the average distance is greater than a hypothetical random distribution, the features are considered dispersed. The index is expressed as the ratio of the observed distance divided by the expected distance (expected distance is based on a hypothetical random distribution with the same number of features covering the same total area) (Clark & Evans, 1954).

To quantify aggregation precisely and meaningfully, the Average Nearest Neighbour Distance ratio (ANN) is used to indicate the aggregation degree. A small ANN indicates a spatial clustering of points, while large ANN value indicates points are dispersed. When ANN is less than 1, points are clustered. If ANN is approximately to 1, points are randomly distributed. When ANN is greater than 1, points are dispersed. The initial

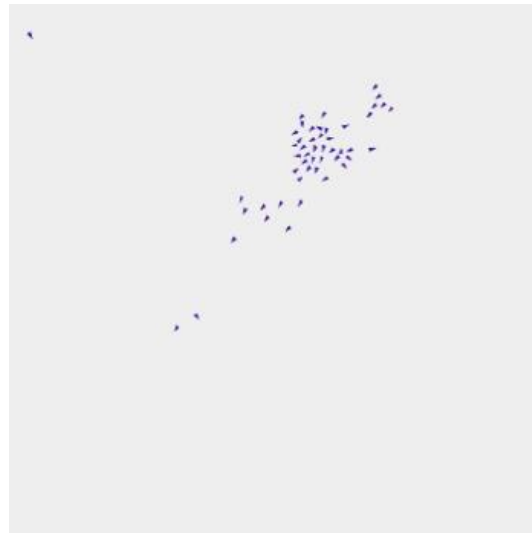
simulation status with randomly scattered carp has an ANN value approximating 1. After the simulation is started, the ANN decreases to less than 1. ANN is calculated at every 250 time steps until up to 3000 time step as showed in Figure13 (1). The related snapshots shown in Figure 13 (2) (ANN = 0.85 at time step of 250) and Figure 13 (3) (ANN = 0.45 at time step of 2500) indicate that smaller ANN values are related to more obvious aggregation.



(1)



(2)



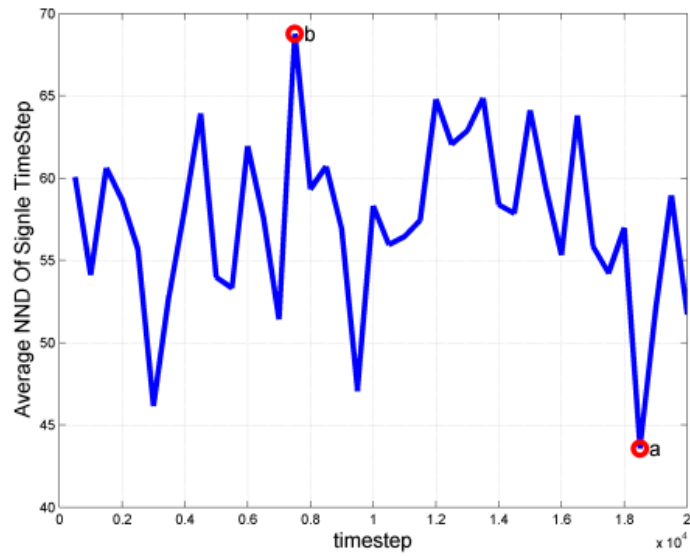
(3)

Figure 13 Plot of Average Nearest Neighbour Distance (ANN) and related snapshots about the simulation of carp aggregation ($n=50$) (1) ANN vs. time: within 3000 time steps (2) Snapshot of carp aggregation status at a (3) Snapshot of carp aggregation status at b

3.2.2 Nearest Neighbour Distance (NND)

Instead of considering only one nearest neighbour carp, average nearest neighbour distance refers to the average of each individual carp's neighbour distance to its three nearest neighbours. Thus the mean of average nearest neighbour distance of single time step ($NND_{singleTimeStep}$) is introduced to quantify the tendency of aggregation for each single time step. As can be seen from Figure 14 (1), $NND_{singleTimeStep}$ is calculated at every 500 time steps until up to 20000 time step. The related snapshots as shown in Figure14 (2) (time step of a) and Figure 14 (3) (time step of b) indicate that smaller $NND_{singleTimeStep}$ values are related to more obvious aggregation.

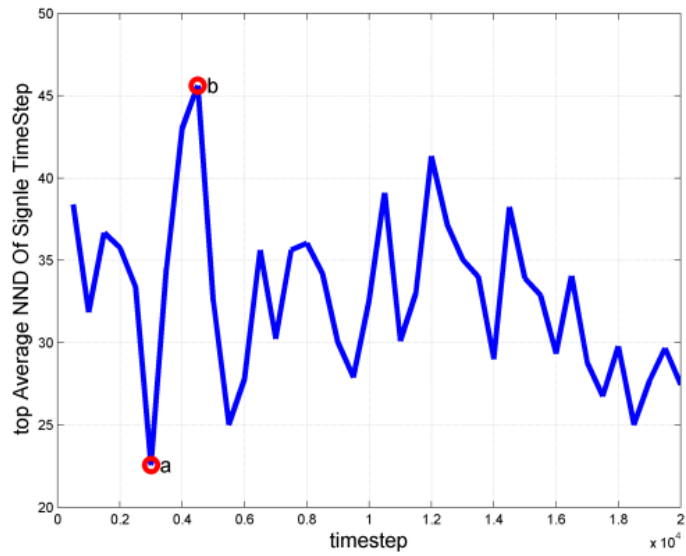
To exclude outliers that linger outside the aggregated group, only the top 60% of individual carp are considered in calculating average nearest neighbour distances, after sorting individual carp's nearest neighbour distance in increasing order. Consequently, we have $topNND_{singleTimeStep}$ to describe aggregation degree and tendency more accurately. $topNND_{singleTimeStep}$ is calculated at every 500 time steps until up to 20000 time steps as showed in Figure 15 (1). The related snapshots as shown in Figure15 (2) (time step of a) and Figure 15 (3) (time step of b) indicate that smaller $topNND_{singleTimeStep}$ values are related to more obvious aggregation.



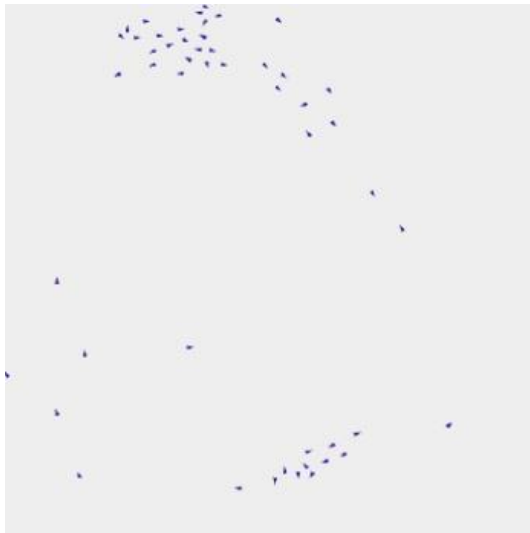
(1)



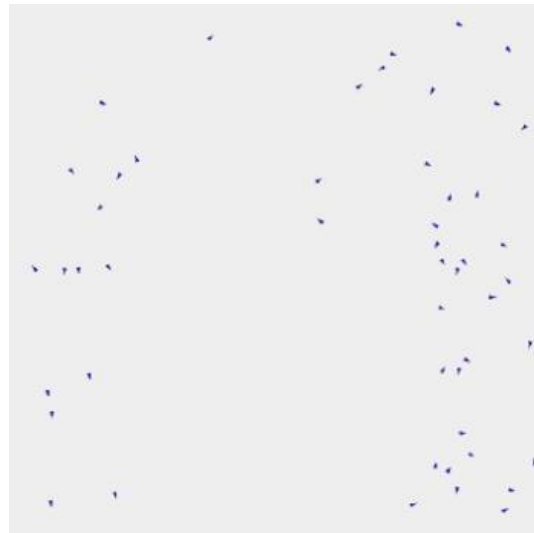
Figure 14 Plot of Average NND of single time step and related snapshots about the simulation of carp aggregation with Temperature Mode On ($n=50$) (1) Average NND single time step vs. time: within 20000 time steps (2) Snapshot of carp aggregation status at a (3) Snapshot of carp aggregation status at b



(1)



(2)



(3)

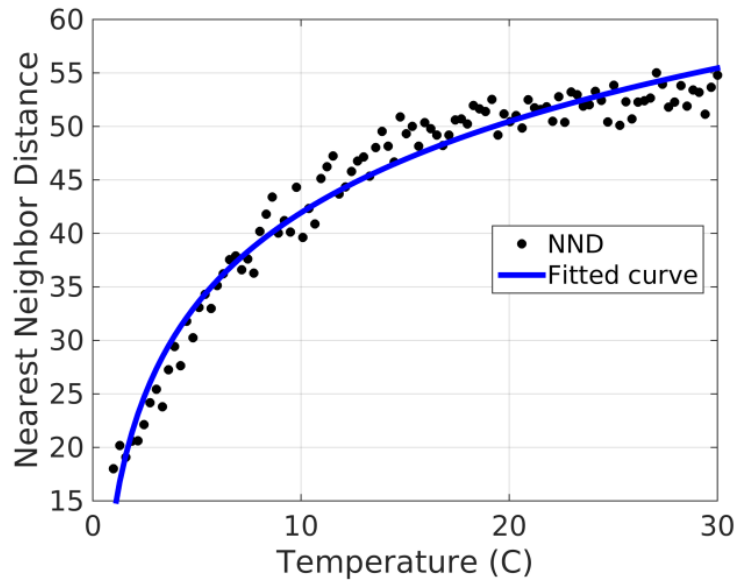
Figure 15 Plot of top Average NND of single time step and related snapshots about the simulation of carp aggregation with Temperature Mode On (n=50) (1) top Average NND single time step vs. time: within 20000 time steps (2) Snapshot of carp aggregation status at a (3) snapshot of carp aggregation status at b

3.3 External factors

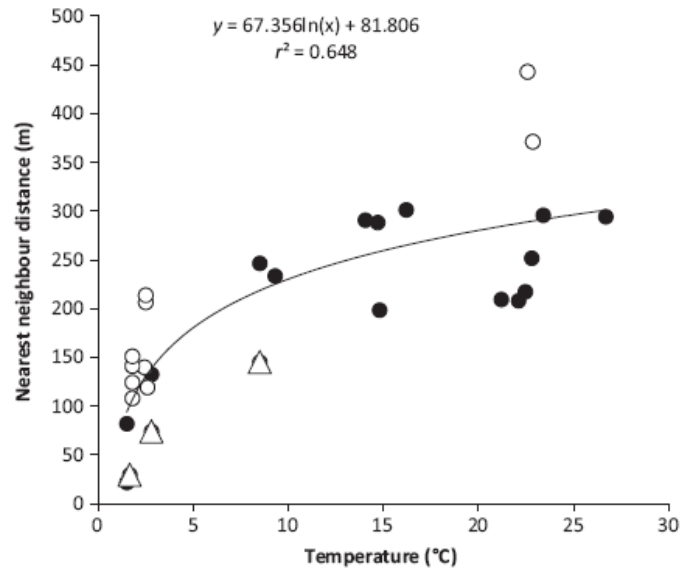
The carp aggregation may be affected by external environmental conditions like water temperature, water flow, water depth, dissolved oxygen, light condition and so forth. These factors might affect inter-carp force fields. According to the observation of common carp in three Midwestern lakes (Bajer et al., 2011), these carp appear to aggregate when water temperatures decline below 10 °C , with particularly tight aggregations occurring below 5 °C . Taking into account that large scale aggregation seems to occur more frequently in low-temperature conditions, we also consider the possible temperature effect on carp aggregation by introducing Temperature Mode in this model. In this case, nearest neighbour distance (NND) is introduced. It refers to the mean value of $NND_{singleTimestep}$ over a certain time frame. In the experiment, fish number is fixed to 50 and the time frame is 20000 time steps. The coefficient in the repel zone is positively related to the temperature, and the one in attraction zone is negatively related to the temperature. As can be seen from Figure 16 (1), with lower temperature, the NND is relatively smaller which indicates greater tendency of aggregation. This simulation result is consistent with the observed relationship between nearest neighbour distance and water temperature in lakes Riley (open circles), Gervais (filled circles) and Lucy (triangles) as showed in Figure 16 (2). A logarithmic relationship was fitted to data combined across lakes ($P < 0.05$) (Bajer et al., 2011). The results from all three lakes were combined and revealed a strong relationship between mean water temperature and carp NNDs. In this case, the NND is the mean distance to five nearest neighbors.

To explore the temperature's influence on aggregation, two simulations of fish groups of 50 with same initial status are run. One is with Temperature Mode on (the center

canvas with the highest temperature, and the edge with the lowest temperature), and the other is with Temperature Mode off. As it can be seen, the aggregation status at a time step of 3000 with Temperature Mode off is different from the one with Temperature Mode on. In the former case, clustered carp are observed near the center of the canvas as showed in Figure 17 (1). In the latter one, clustered carp are observed near the edge of the canvas, where the temperature is relatively lower than it is near the center as showed in Figure 17 (2).

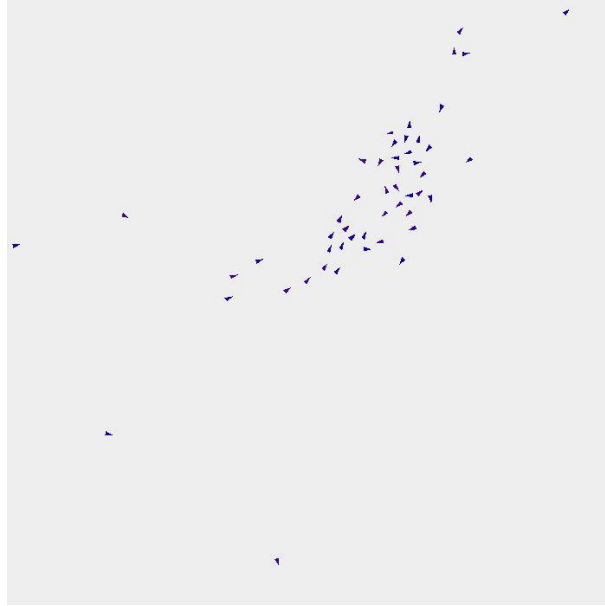


(1)

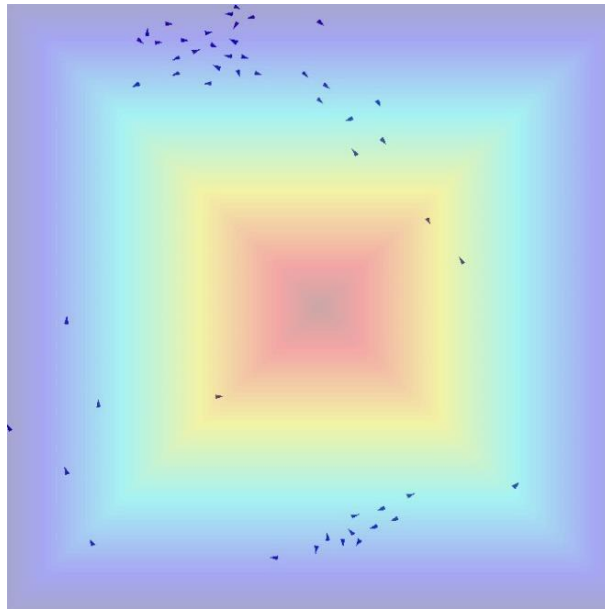


(2)

Figure 16 NND vs. Temperature (1) Experiment Data from simulation results (n=50) within 20000 time steps (2) Real observed data



(1)



(2)

Figure 17 Snapshots about the simulation of carp aggregation with Temperature Mode On/OFF (n=50/Time step=3000) (1) Aggregation status with Temperature Mode OFF (2) Aggregation status with Temperature Mode ON

3.4 Irregular Boundary

The pilot experiment is carried out on a simple square canvas to simulate the aggregation. However, it is more common to find irregular-shaped lake in the real world. The irregular domain complicates the boundary problem. In this model, we also fixed the boundary problem by using `IrgBMode`. Figure 18 shows the simulation of the aggregation of carp in an irregular boundary. Instead of being reflected, fish that hit the wall are bounced back in the opposite direction and keep the same velocity. In this case, we set $\varepsilon = 5e-2$ in the repel zone, $\varepsilon = 5e4$ in the attraction zone, and 50 for fish group size in the simulation. The results are captured for every 5000 time steps ($dt = 1e-2$).

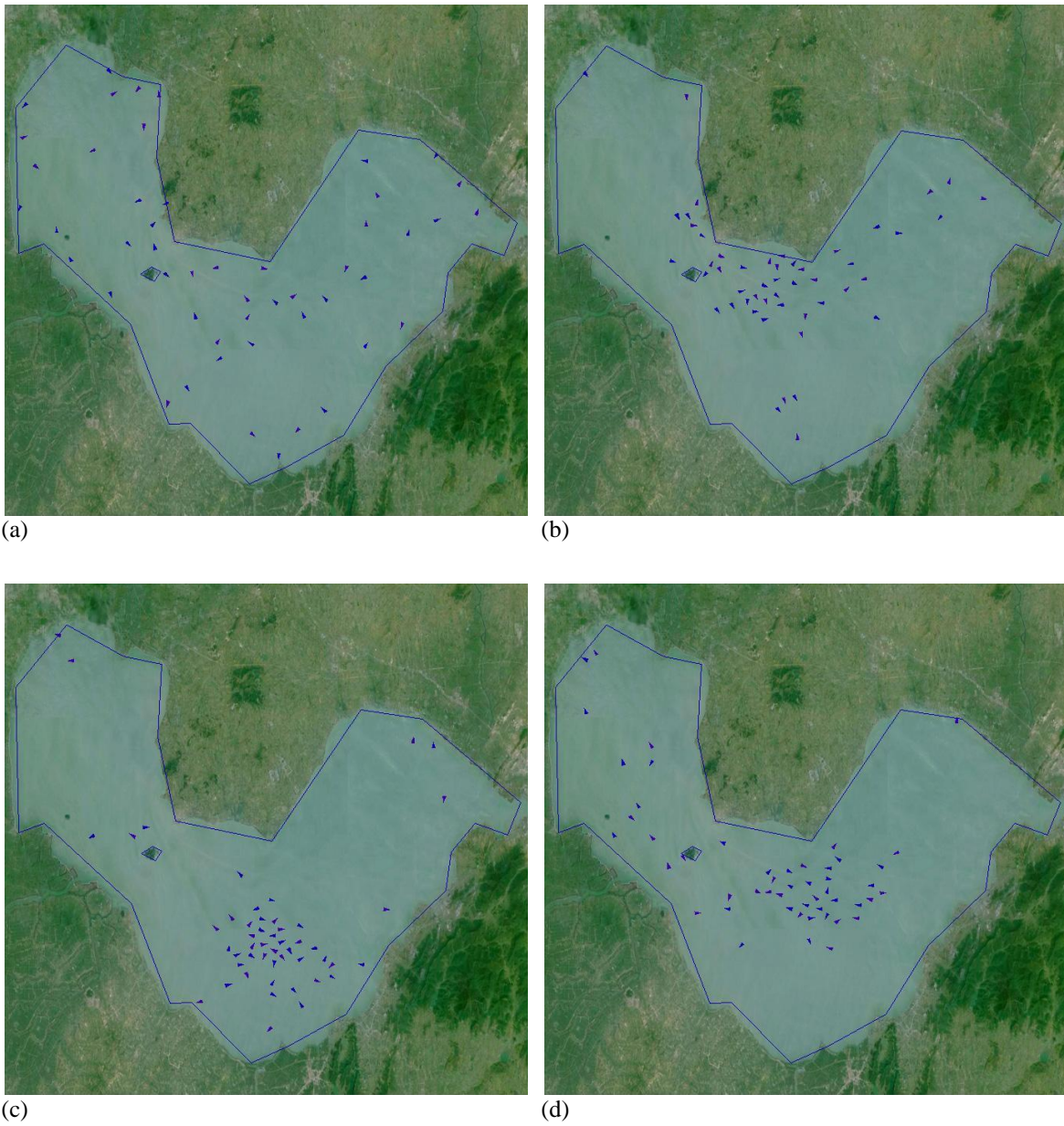


Figure 18 Snapshots about the simulation of carp aggregation with IrgBMode On ($n=50$)
 (a) Initial status. (b) Snapshot at time step of 5000 (c) Snapshot at time step of 10000. (d)
 Snapshot at time step of 15000

CHAPTER 4

SUMMARY AND FUTURE WORK

The motivation of controlling the populations of Asian carp led to the investigation of the collective behaviour of Asian carps such as aggregation. This paper proposed a molecular dynamics based model to formulate the aggregation of Asian carps. In this simulation, each carp changes its direction and velocity after one time step. Its new direction and velocity depend on the positions, orientations and velocities of a number of neighbouring carp that are in its perceivable distance. Thus the neighbouring carp that is located in its out-of-perception zone and blind zone will be excluded from consideration. The influence of a neighbour depends on its relative position. The influence zone is divided into attraction zone, parallel zone, repulsion zone as well as blind zone. Correspondingly, the pair-wise inter-carp forces, an analogy of van der Waals forces, vary in different zones. To cater high-order interaction, a force related to individual carp's velocity is introduced to balance the interaction between more than two carp. Other than the consideration of internal interactions, the effect of external factors like temperature on group behaviour is investigated in the model. Furthermore, boundary limitation is also incorporated to exercise the model's possible applications in the real world.

Preliminary simulations about the aggregation of a small number of carp within simple

environments are investigated. The aggregation phenomenon like swarm, parallel groups, and merge of different groups are observed in the simulation. To quantify the aggregation, Average Nearest Neighbour Distance ratio (ANN) and mean of average nearest neighbour distance of single time step (NNDsingleTimestep) are used to describe the degree of aggregation in each time step. In the Temperature Mode of the model, the Nearest Neighbour Distance (NND), which refers to the mean value of NNDsingleTimestep over a certain time frame, is used to characterize the influence of temperature on aggregation. According to the simulation results, NND obtained during high temperature is larger than that obtained during lower temperature. The carp aggregation tends to happen at the location with lower temperature, which is consistent with observed data. Other than considering the external factors that influence aggregation behaviour like temperature, the irregular boundary problem is also investigated. The aggregation phenomenon can also be achieved in an irregular domain. In the preliminary simulation results, the motivations of fish aggregation, such as foraging advantages, reproductive advantages, predator avoidance, or hydrodynamic efficiency, are not considered yet.

To achieve a more robust model, future work is needed:

1. A more complex model that incorporates other both internal and external factors that would possibly influence carp behaviour, such as lateral line, body mass. Environment factors, like dissolved oxygen, water velocity and light condition might also need to be considered in the model. At the current stage, the addressed mathematical model only focuses on a two-dimensional scenario. It might gain more potential in practical use if it is developed into a three-dimensional model.

2. Further experiment-based validation about the mathematical model needs to be made in our future work. The information about the interaction between neighbouring carp, like radius of repulsion zone, parallel zone, attraction zone and blind angle would facilitate the optimization of the model. The real-time movement and aggregation status of carp schools, such as the density of a carp school, velocity of the centroid of a carp school, radius of a carp school as well as the coordinate value of the centroid of carp school, would be useful in a trajectory prediction about the motion and aggregation of carp. Furthermore, the collision of carp is a very important process in our model. In order to disclose the mechanism of collision, the velocity and geometric configuration of carp schools before and after collision would be required. In addition, the determination of the parameters of the mathematical model can be achieved by formulating the experiment-based validation as an inverse problem. Given appropriate gradient information and optimization algorithms, the parameters may be quickly adjusted for different real-time data (Lin, Anderson, Newman III, & Zhang, 2016; Lin, Newman III, & Anderson, 2016).

A completely accurate and deterministic prediction about the aggregation of carp is impossible. However, with certain data collection, the mathematical model addressed in this work might approximately estimate short-term aggregation behaviours.

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