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原著論文

Article

Searching Strategies with Low Computational Costs for Multiple-Vehicle Bike Sharing System Routing Problem

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Abstract: We have already proposed a multiple-vehicle bike sharing system routing problem (mBSSRP) to adjust the number of bicycles at each port using multiple vehicles in short time. However, there are many strict constraints in the mBSSRP, thus it is difficult to obtain feasible solutions of the mBSSRP for some instances. To obtain feasible solutions of the mBSSRP, we have proposed a mBSSRP with soft constraints (mBSSRP-S) that removes some constraints from mBSSRP and appends violations to an objective function as penalties, and a searching strategy that explores both the feasible and infeasible solution spaces. Numerical experiments indicated that solving mBSSRP-S to obtain feasible solutions of mBSSRP results in better performance than solving mBSSRP directly. However, mBSSRP-S includes infeasible solutions of mBSSRP, thus the neighborhood solutions and computational costs increase. In this study, we propose search strategies with low computational costs while maintaining performance. In particular, we propose two search strategies: the first one is to reduce neighborhood solutions to obtain a feasible solution in a short time before finding a feasible solution of the mBSSRP, and the second one is to change the problem to be solved (mBSSRP or mBSSRP-S) after a feasible solution is obtained and to search good near-optimal solutions in a short time. As the first search strategy, we propose two search methods for reducing the number of neighborhood solutions in the Or-opt and the CROSS-exchange and compare their performance with our previous results. From numerical experiments, we confirmed that a feasible solution can be obtained within a short time by exploring only the normal order insertion of the Or-opt and the normal order exchange of the CROSS-exchange as the neighborhood solutions. Next, as the second search strategy after a feasible solution of mBSSRP is obtained, we propose four search methods and compare their performance with our previous results. Numerical experiments show that the search method that only searches for the normal order insertion of the Or-opt and the normal order exchange of the CROSS-exchange with hard constraints after obtaining a feasible solution can obtain short tours within a short time.

Keywords: bicycle sharing system; combinatorial optimization problem; tabu search; low computational costs; Or-opt; CROSS-exchange



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1. Introduction

Bicycle sharing systems (BSSs) have been introduced in many cities around the world as a new public transportation system. Currently, more than 1,700 programs of BSSs are operating in the world [1], for instance, BIXI in Montréal [2], Velib' in Paris [3], docomo bike share in Tokyo [4], citybike in Vienna [5], Citi Bike in New York [6], Capital bikeshare in Washington D.C. [7], BULEbikes in Boston [8] and Bicing in Barcelona [9].

A BSS consists of many distributed automatic rental ports and many rental bicycles. A registered user can rent a bicycle at a port, use it for a short trip and return it to a different port. A BSS is not only a convenient service, but also it can reduce greenhouse gas and traffic congestion issues. For example, Zhang et al. (2018) [10] have estimated that the introduction of a BSS at Shanghai saved 8358 tonnes of petrol, and reduced CO₂ and NO_x emissions 25,240, and 64 tonnes, respectively in 2016.

In a BSS, almost all ports are in either an empty or full state after a while. An empty bicycle port implies that a user cannot rent a bicycle, whereas a full bicycle port implies that a user cannot return a bicycle. Thus, full or empty states lead to dissatisfaction of users. In addition, broken bicycles are left unattended. Consequently, users' frustration is further increased. To address these issues, several capacitated vehicles need to relocate bicycles among ports so that sufficient bicycles are available at each port. If operators can execute repositioning works efficiently, users will not have experience that they cannot rent or return bicycles and BSS companies can reduce labor costs and carbon emissions of vehicles. Thus, both users and BSS companies benefit.

Recently, many studies have been conducted on repositioning bicycles of a BSS. The repositioning of BSS can be divided into two cases.

The first one is a static case. In the static case problem, the number of bicycles does not change at each port while the bicycles are restored by the vehicle, because the system assumes that the bicycles are not moving much at midnight or after operation hours. As for the static case problem, Dell'Amico et al. (2014) [11] proposed a bike sharing rebalancing problem (BRP) and formulated BRP as a mixed integer linear programming problem, and they solved BRP using the branch-and-cut algorithm for the 22 real world instances collected from the web sites. Then, they proposed a destroy and repair algorithm for the BRP, and tested their algorithm on benchmark instances [12]. Although these studies [11,12] are interesting, they did not consider a time limit constraint: vehicles must return to a depot within a given time limit. Then, it is not guaranteed that all operations will be finished within the working hour in BRP.

On the other hand, Rainer-Harbach et al. (2013) [13] proposed a general variable neighborhood search (VNS) with an embedded variable neighborhood descent for finding efficient vehicle tours of a balancing bicycle sharing system (BBSS). In the BBSS, they considered the time limit constraint, and that a vehicle can visit a port multiple times. Then, they tested their algorithm on benchmark instances of real-world data provided by Citybike in Vienna with up to 90 ports, and the result of numerical experiments showed that their algorithm obtained good solutions in a reasonable time. In addition, Raidl et al. (2013) [14] proposed efficiently determining optimal loading operation of VNS method for finding efficient vehicle tours of the BBSS. They tested the same instances with Rainer-Harbach et al. (2013), and they reported that their method showed better performance than the original VNS. Moreover, Papazek et al. (2013) [15] also address the BBSS, and they proposed two GRASP (Greedy Randomized Adaptive Search Procedure) heuristic approaches and conducted numerical experiments by varying sizes of instances that ranged from 30 to 700. The numerical experiments show that combined PILOT (Preferred Iterative Look Ahead Technique) and GRASP method obtained good performance than VNS for large size instances. In the BBSS, when vehicles start and come back to a depot, the vehicles must be empty. However, if broken bicycles are found in the process of rebalancing operation, they must be repaired at the depot after the rebalancing operation, because the depot has many spare bicycles. Thus, the constraint that vehicles must be empty when vehicles start and come back to the depot is not realistic [13–15].

The second one of the repositioning of the bicycle sharing system is a dynamic case. In the dynamic case problem, the number of bicycles is changed at each port while the bicycles are restored by the vehicle. Kloimüller et al. (2014) [16] extended the BBSS to a dynamic case problem, and proposed a model of a dynamic balancing bicycle sharing system (DBBSS). Then, they applied their previous approach to the DBBSS. The numerical experiments showed that their approach was also effective to DBBSS. Chiariotti et al.

(2018) [17] also addressed the dynamic case problem. Then, they tested instances with 280 ports generated by New York City's CitiBike, and the result of numerical experiments showed that their dynamic strategy obtained better performance than static approach. In the numerical experiments for the dynamic repositioning of BSS, Kloimüller et al. (2014) and Chiariotti et al. (2018) used Vienna and New York City's data, respectively. However, it is not clear whether their approaches can be applied to other cities. Table 1 summarizes the related literatures.

Table 1. Summary of the related literatures.

Paper	Static or Dynamic	Maximum Number of Port Size
Rainer-Harbach et al. (2013)	static	90
Raidl et al. (2013)	static	90
Papazek et al. (2013)	static	700
Kloimüller et al. (2014)	dynamic	90
Dell'Amico et al. (2014)	static	116
Dell'Amico et al. (2016)	static	564
Chiariotti et al. (2018)	dynamic	280
This study	static	100

In our previous study, we formulated a new bicycle sharing system routing problem as “multiple-vehicle bike sharing system routing problem (mBSSRP).” The mBSSRP finds tours within the shortest travel time when multiple vehicles load and unload bicycles at each port. In the mBSSRP, we consider the time limit constraint, and vehicles can start and finish at the depot with bicycles. Although we treated the static case problems, the mBSSRP is close to a real-life situation. As a result of solving the mBSSRP using a mixed-integer linear programming (MIP) solver [18], an optimal solution is obtained for small-size instances. However, we cannot obtain an optimal solution for large-size instances within a reasonable time frame. Thus, we proposed local search methods to obtain approximate solutions of mBSSRP within a short time [19]. Nevertheless, owing to some strict constraints of mBSSRP, the proposed methods could not obtain feasible solutions for some instances. Therefore, we proposed a “multiple-vehicle bike sharing system routing problem with soft constraints (mBSSRP-S)” that removes some constraints from the mBSSRP and appends violations of the mBSSRP to the objective function as penalties [20]. In Ref. [20], we also proposed a method that controls the execution of the Or-opt [21] and the CROSS-exchange [22] with the tabu search method [23–25] for solving mBSSRP and mBSSRP-S. Numerical experiments show that solving mBSSRP-S to obtain feasible solutions of mBSSRP achieves good performance when compared to solving directly mBSSRP [20]. However, computational costs increase because neighborhood solutions increase as a result of including infeasible solutions of mBSSRP. Thus, it is necessary to reduce the computational costs while maintaining the performance.

Regarding the reduction in computational costs, there are several discussions for the combinatorial optimization problems. For example, Hasegawa et al. (2002) [26] and Matsuura et al. (2008) [27] introduced a method of limiting the search space to short paths when they solved the TSP (Traveling Salesman Problem). In particular, Hasegawa et al. (2002) used only the 10% nearest neighbors of the cities. Then, Matsuura et al. (2008) used only the near neighbors of the cities. This is because most good TSP solutions have short paths. Motohashi et al. (2008) [28] used a neighborhood list to efficiently solve the TSP. Moreover, Motohashi et al. (2009) [29] used two different candidate lists, that is, the nearest neighbors and quadrant neighbors to solve a large scale TSP. Finally, Taillard et al. (2019) [30] showed that the computational costs of heuristic methods can be significantly reduced by constructing a set of edges that are considered to be included in the optimal solution at first.

Regarding the BSS, Pal et al. (2016) [31] used a candidate list based on nearest neighbors to efficiently solve the static complete rebalancing problem. Then, Dell’Amico et al. (2016) [12] used some formulations to determine whether constraints are satisfied or not to speed up the computation of bike sharing rebalancing problem. Thus, it is important to reduce the computational costs for finding a good rebalancing tour of the BSS, because a BSS has hundreds of ports and it is not practical to wait for hours to find a rebalancing tour of the BSS. Then, the goal of this study is to propose efficient search strategies with low computational costs while maintaining the performance of the mBSSRP.

To reduce computational costs in this study, we focused on the search process and investigated the rate of the Or-opt and the CROSS-exchange executions. The execution rate of the Or-opt that inserts ports in the normal order was 66%, that of the CROSS-exchange that exchanges ports in the normal order was 20%, and the reverse orders of insertion of the Or-opt and exchange of the CROSS-exchange were rarely executed. In addition, we found that once a feasible solution of the mBSSRP is obtained, our conventional method [20] searches for the feasible solutions successively.

From these results of the investigation, in this paper, we propose two search strategies: the first one is to reduce neighborhood solutions to obtain a feasible solution in a short time before finding a feasible solution of the mBSSRP from the mBSSRP-S, and the second one is to change the problem to be solved (mBSSRP or mBSSRP-S) after a feasible solution is obtained and to search good near-optimal solutions in a short time. As the first search strategy, we propose two search methods for reducing the number of neighborhood solutions in the Or-opt and the CROSS-exchange, and compare their performance with our previous results. The results of the numerical experiments indicate that by limiting the neighborhood solutions to the normal order insertion of the Or-opt and the normal order exchange of the CROSS-exchange, we obtained feasible solutions within a short time while maintaining the performance.

Next, as the second search strategy after obtaining a feasible solution, we proposed four methods in which the searching space is further reduced. The problem to be solved is changed from mBSSRP-S to mBSSRP to explore only feasible solutions. The results of the numerical experiments show that by reducing the number of the neighborhood solution, only searching for the normal order insertion of the Or-opt and the normal order exchange of the CROSS-exchange with hard constraints after obtaining a feasible solution can obtain short tours within a short time. From these numerical experiments, we have succeeded in reducing the computational time while maintaining the performances. Furthermore, we found that after finding a feasible solution, we could find short tours within a short time by solving the hard constraint problem instead of the soft constraint problem.

This paper is structured as follows. In Section 2, we describe the mBSSRP and mBSSRP-S. In Section 3, we present the heuristic method. Then, Section 4 presents the computational costs reduction method. Numerical experiments are reported in Section 5. Finally, conclusions and future works are provided in Section 6.

2. Problem Description

To determine tours that efficiently relocate bicycles using multiple vehicles, we have already proposed mBSSRP and mBSSRP-S [20]. In mBSSRP, the search is executed with satisfying hard constraints of the time and capacity of the vehicles. In mBSSRP-S, these constraints are removed and violations of these constraints are added to the objective function as penalties.

In mBSSRP and mBSSRP-S, given are one depot, n ports and m vehicles. Each port is classified into two types: pickup and delivery ports. In the pickup ports, the number of bicycles is excess and bicycles must be loaded on the vehicle. In the delivery ports, the number of bicycles is lack and bicycles must be delivered. In mBSSRP and mBSSRP-S, vehicles relocate the bicycles from the pickup port to the delivery port. The rules of mBSSRP and mBSSRP-S as follows:

- (1) The vehicles can load bicycles at the depot, because the depot has spare bicycles available.
- (2) All vehicles must leave the depot and return to the depot.
- (3) The number of bicycles does not change during the repositioning process.
- (4) Each port can be visited only once by one vehicle.

Under these rules, reposition of bicycles is executed using vehicles. For details, we refer to Tsushima et al. [20].

2.1. Multiple-Vehicle Bike Sharing System Routing Problem (mBSSRP)

In addition to the rules, the solution of the mBSSRP must satisfy the following two constraints:

- (i) time limit constraint: vehicles must return to the depot within the time limit.
- (ii) capacity constraint: vehicles cannot load more bicycles than their capacity, and the capacity of a vehicle cannot be less than zero.

The purpose of the mBSSRP is to find the tour that minimizes the total travel time of the vehicles among the routes that satisfy the rules (1) to (3) and the constraints of (i) and (ii).

2.2. Multiple-Vehicle Bike Sharing System Routing Problem with Soft Constraints (mBSSRP-S)

In the mBSSRP-S, the hard constraints i) and ii) are removed from mBSSRP and these constraints are added to the objective function as penalties if they are violated. Then, the objective function of mBSSRP-S is defined as follows:

$$\text{minimize} \quad T + \alpha \times P_T + \beta \times (P_{B+} + P_{B-}) \quad (1)$$

where T denotes the total travel time and is the objective function of mBSSRP, P_T denotes the time that vehicles worked over the time limit, P_{B+} and P_{B-} are the number of bicycles that could not be loaded or supplied, and α and β are the weight coefficients of the penalty. If P_T , P_{B+} and P_{B-} are equal to zero, the solution is a feasible solution for mBSSRP.

3. Heuristic Methods

To obtain good approximation solutions of mBSSRP, we proposed a method using the tabu search method [23–25]. In the proposed method [20], first, we generate an initial solution by the construction method based on the farthest insertion method. Second, we improve the initial solution by the local searches: the inserting method and the swapping method. Finally, good approximate solutions are searched by the tabu search method, which is one of the metaheuristic methods. The neighborhood solution of the tabu search is constructed by the Or-opt and the CROSS-exchange. Figure 1 represents the flow of the proposed method.

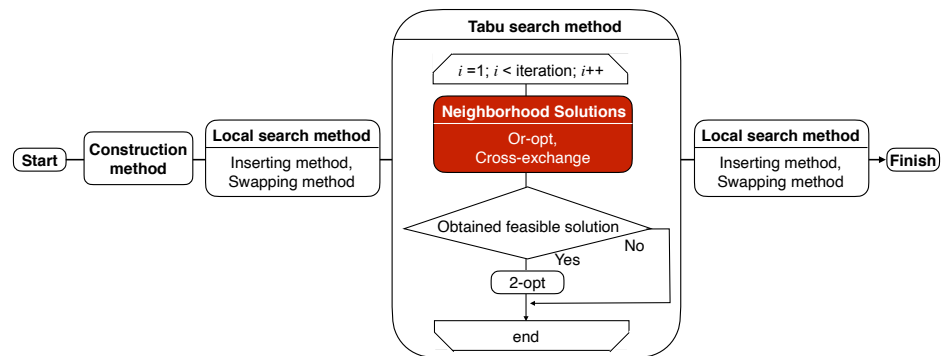


Figure 1. Flow of the proposed framework [20]. First, we construct an initial tour using the construction method. Then, we improve the initial tour using the inserting and the swapping method. Next, the Or-opt and the CROSS-exchange are controlled by the tabu search and aim to transition to a feasible solution of mBSSRP. The red rectangle corresponds to the computational cost reduction part. The details are described in Section 4. After feasible solutions of mBSSRP are obtained in the tabu search process, the 2-opt is executed. If we cannot obtain a feasible solution, the 2-opt method is not executed. Finally, to obtain better solutions, we executed the inserting and the swapping method again.

3.1. Construction Method for Generating an Initial Solution

First, to generate an initial solution, we use the construction method based on the farthest insertion method. It is often used as one of the construction methods for the combinatorial optimization problem. The procedure of the construction method is described as follows:

1. We randomly select p ports, where p denotes the number of available vehicles.
2. Each vehicle constructs a subtour with the depot and one of the selected p ports.
3. An unvisited port k , which is the farthest from the depot, is selected.
4. The port k is inserted between ports i and j in the subtour where $\Delta_{ikj} = t_{ik} + t_{kj} - t_{ij}$ is minimized.
5. Steps 3 and 4 are repeated until all ports are visited once by one vehicle.

When we solve mBSSRP, we continue this operation while the constraints of mBSSRP are satisfied. On the other hand, when we solve mBSSRP-S, we consider only the travel time between ports i and j .

3.2. Local Search Methods for Improving the Initial Solution

To improve the initial solutions, we use the following two local search methods: the inserting method and the swapping method. The inserting and the swapping methods improve a single tour. The inserting and the swapping methods are used after constructing an initial tour and after improving the tour by the tabu search.

In the inserting method, a partial tour $i - j$, whose length covers a maximum of three ports in a tour is inserted into an edge (k, l) in the same tour (Figure 2). Then, there are two types of insertion operations as follows: the normal order (Figure 2b) and the reverse order (Figure 2c).

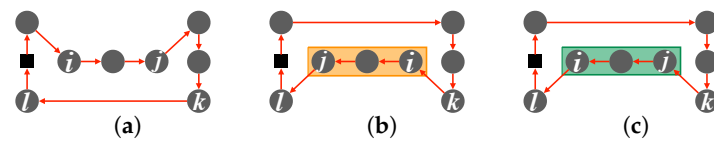


Figure 2. Example of the inserting method. Black squares represent depots and gray circles represent ports. (a) A tour before the inserting method is executed. (b) A partial tour $i-j$ is inserted into $k-l$ as the normal order (the orange rectangle). (c) The partial tour $i-j$ is inserted into $k-l$ as the reverse order (the green rectangle).

The swapping method swaps a partial tour $i-j$ for a partial tour $k-l$ (Figure 3). Then, there are four types of swapping operations: both partial tours $i-j$ and $k-l$ are exchanged with the normal order (Figure 3b), only the tour $i-j$ is the reverse order (Figure 3c), only the tour $k-l$ is the reverse order (Figure 3d), and both partial tours $i-j$ and $j-k$ are exchanged with the reverse order (Figure 3e).

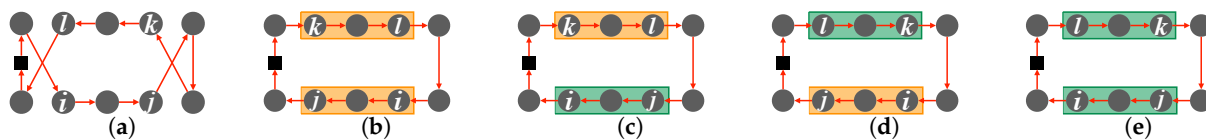


Figure 3. Example of the swapping method. Black squares represent depots and gray circles represent ports. (a) A tour before the swapping method is executed. (b) Both partial tours $i-j$ and $k-l$ are exchanged with the normal order (the orange rectangles). (c) Only a partial tour $i-j$ is exchanged in the reverse order (the green rectangle). (d) Only a partial tour $k-l$ is exchanged in the reverse order (the green rectangle). (e) Both partial tours $i-j$ and $k-l$ are exchanged with reverse order (the green rectangles).

3.3. Method by Using the Tabu Search

In the local search methods, a solution moves to only good solutions that are better than the current solution. Thus, the solutions get stuck at local optimal solutions. To escape from the local optimal solutions, we use the tabu search method in this study as well as in our previous study [20]. Namely, we used the tabu search to propose search strategies with low computational costs while maintaining the performance for the mBSSRP in this study. The tabu search is one of the powerful meta-heuristic strategies for solving the combinatorial optimization problem. The tabu search is successively used for the vehicle routing problem, which is a similar combinatorial optimization problem to mBSSRP. Moreover, the tabu search also has some advantages, because it has few parameters, leads to easy implementation and has low computational costs. To avoid repetitive operations, a tabu list is used in the tabu search. The tabu list records the previous search history. Thereafter, the solution in the tabu list cannot be selected for a certain temporal duration. This duration is known as a tabu tenure.

In this study, a current solution moves to the best neighborhood solution generated by the Or-opt and the CROSS-exchange. The Or-opt and the CROSS-exchange methods improve the total length of the tours using two different tours. The Or-opt inserts a partial tour $i-j$ of a tour in an edge (k,l) in another tour (Figure 4). There are two types of insertions: the normal order (Figure 4b) and the reverse order (Figure 4c). The CROSS-exchange replaces a partial tour $i-j$ in one tour with a partial tour $j-l$ in the other tour (Figure 5). There are four types for swap operations: both partial tours $i-j$ and $k-l$ are exchanged in the normal order (Figure 5b); the partial tour $i-j$ is in the normal order, and the partial tour $k-l$ is in the reverse order (Figure 5c); the partial tour $i-j$ is in the reverse order, and the partial tour $k-l$ is in the normal order (Figure 5d); and both partial tours $i-j$ and $k-l$ are exchanged with the reverse order (Figure 5e). If a neighborhood solution of the CROSS-exchange that exchanges the partial tours $i-j$ and $k-l$ is selected, the combination i and k is memorized in the tabu list. If a neighborhood solution of the

Or-opt is selected that inserts the partial $i - j$ into the edge (k, l) is selected, the combination i and k is memorized. Thus, the selection of the neighborhood solution that connects port i and port k is prohibited during a certain temporal iteration.

If a feasible solution of mBSSRP is found, the 2-opt method is executed to obtain better solutions than the current one. The 2-opt method replaces two edges by two other edges (Figure 6). If we have never obtained a feasible solution of mBSSRP at once in the tabu search process, the 2-opt method is not executed.

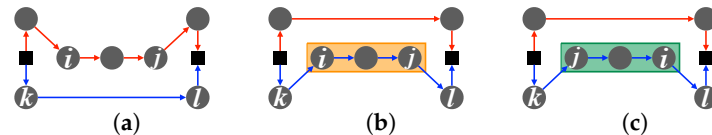


Figure 4. Example of the Or-opt. Black squares represent depots and gray circles represent ports. The red and blue lines represent each tour. (a) Tours before the Or-opt is executed. (b) A partial tour $i - j$ is inserted into another tour $k - l$ in the normal order (the orange rectangle). (c) The partial tour $i - j$ is inserted into another tour $k - l$ in the reverse order (the green rectangle).

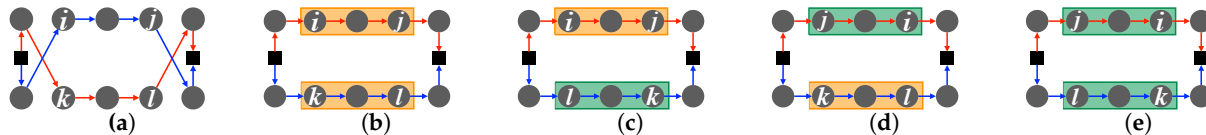


Figure 5. Example of the CROSS-exchange. Black squares represent depots and gray circles represent ports. Orange rectangles express normal order and green rectangles express a reverse order. Red and blue lines represent each tour. (a) Tours before the CROSS-exchange is executed. (b) Partial tours $i - j$ and $k - l$ are exchanged with the normal order. (c) Only the partial tour $k - l$ is exchanged in the reverse order. (d) Only the partial tour $i - j$ is exchanged in reverse order. (e) Partial tours $i - j$ and $k - l$ are exchanged in the reverse order.

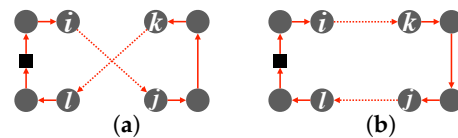


Figure 6. Example of the 2-opt method. Black squares represent depots and gray circles represent ports. (a) A tour before the 2-opt method is executed. (b) A tour after the 2-opt method is executed.

3.4. Dynamically Changing Weight of Penalties

To move good solutions of mBSSRP from the solution of the mBSSRP-S, we must set appropriate values of the weight parameters α and β in the objective function (Equation (1)) of the mBSSRP-S. If we set the parameters to small values, we cannot obtain feasible solutions owing to the small values of the parameters. Because the penalty becomes weak even when the solution has many constraint violations. Meanwhile, if we set the parameters to large values, the power of the parameters will be excessively strong, which is the same situation for solving mBSSRP. Thus, we dynamically change the parameters α and β according to the solution state.

To adjust the weight parameters α and β dynamically, the objective function of the mBSSRP-S was modified as follows:

$$\text{minimize} \quad T(t) + \alpha(t) \times P_T(t) + \beta(t) \times (P_{B+}(t) + P_{B-}(t)) \quad (2)$$

where $\alpha(t)$ and $\beta(t)$ represent weight parameters for the time limit, loading and supplying constraints at the t th iteration, $T(t)$ denotes the total travel time at the t th iteration, $P_T(t)$ denotes the excess working time beyond the time limit at the t th iteration, $P_{B+}(t)$ denotes

the loading violation of the bicycles at the t th iteration and $P_{B-}(t)$ denotes the supplying violation of the bicycles at the t th iteration.

The adjustment of the parameters is determined by comparing $\alpha(t) \times P_T(t)$ and $\beta(t) \times (P_{B+}(t) + P_{B-}(t))$ at the t th iteration. If the penalty of the time limit $\alpha(t) \times P_T(t)$ is larger than the sum of penalties loading and supplying constraints $\beta(t) \times (P_{B+}(t) + P_{B-}(t))$, $\alpha(t)$ is increased and $\beta(t)$ is decreased. If the penalty $\beta(t) \times (P_{B+}(t) + P_{B-}(t))$ is larger than $\alpha(t) \times P_T(t)$, $\alpha(t)$ is decreased and $\beta(t)$ is increased. If $P_T(t) = 0$ or $P_{B+}(t) + P_{B-}(t) = 0$, a corresponding weight $\alpha(t)$ or $\beta(t)$ is not updated. Then, the followings are used for adjusting the parameters:

if $p_T(t) = 0$,

$$\alpha(t+1) = \alpha(t), \quad (3)$$

otherwise

$$\alpha(t+1) = \begin{cases} \alpha(t) & \text{if } \alpha(t)p_T(t) = \beta(t)(p_{q+}(t) + p_{q-}(t)), \\ \lambda\alpha(t), & \text{if } \alpha(t)p_T(t) > \beta(t)(p_{q+}(t) + p_{q-}(t)), \\ \mu\alpha(t), & \text{if } \alpha(t)p_T(t) < \beta(t)(p_{q+}(t) + p_{q-}(t)), \end{cases} \quad (4)$$

and if $p_{q+}(t) + p_{q-}(t) = 0$,

$$\beta(t+1) = \beta(t), \quad (5)$$

otherwise

$$\beta(t+1) = \begin{cases} \beta(t), & \text{if } \alpha(t)p_T(t) = \beta(t)(p_{q+}(t) + p_{q-}(t)), \\ \lambda\beta(t), & \text{if } \alpha(t)p_T(t) < \beta(t)(p_{q+}(t) + p_{q-}(t)), \\ \mu\beta(t), & \text{if } \alpha(t)p_T(t) > \beta(t)(p_{q+}(t) + p_{q-}(t)), \end{cases} \quad (6)$$

where λ is an increasing parameter ($\lambda > 1$) and μ is a decreasing parameter ($0 < \mu < 1$). If the value of the weights is less than 1.0, the weights are set to unity ($\alpha(t+1) = 1$ or $\beta(t+1) = 1$).

4. Computational Cost Reduction Method

To reduce neighborhood solution and computational costs, we investigate the percentage of the Or-opt and the CROSS-exchange executions used in the tabu search part. The feasible neighborhood solutions of the mBSSRP-S include the infeasible neighborhood solutions of the mBSSRP. Therefore, when we solve the mBSSRP-S, it takes more time to determine the next solution than in the case of mBSSRP. To reduce the computational cost of solving mBSSRP-S, we need to remove unnecessary neighborhood solutions. The percentage of the insertion and exchange operations performed by the proposed method was approximately 66% for the Or-opt, which inserts ports in the normal order (Figure 4b), and approximately 20% for the CROSS-exchange, which exchanges ports in the normal order (Figure 5b), implying that the reverse order of insertion and exchange was rarely executed. Thus, we did not search for less frequently performed reverse order operations to reduce the computational costs. In our previous study, we have shown that once a feasible solution of the mBSSRP is obtained, the proposed method searches for the feasible solutions successively [20]. Next, to find a good feasible solution of the mBSSRP, we examine whether we should change the problem to be solved (mBSSRP or mBSSRP-S) before and after a feasible solution is obtained.

Table 2 summarizes the search strategy before obtaining a feasible solution of the mBSSRP. We propose two search methods (1B-S and 1C-S) in this case. In Table 2, the first search method 1A-S searches for all neighborhood solutions of the Or-opt and the CROSS-exchange. Thus, this search method is the same as the conventional search method [20]. The second search method 1B-S only explores insertion of the normal order of the Or-opt which is the most executed (Figure 4 b). The third search method 1C-S searches for the insertion of

the normal order of the Or-opt and exchange of the normal order of the CROSS-exchange (Figures 4b and 5b). The goal of the search methods before obtaining a feasible solution is to find a feasible solution within a short time for all trials.

In addition, to further reduce the computational costs the search strategy is changed after a feasible solution of mBSSRP is obtained. In this paper, we propose four new search methods (2B-S, 2B-H, 2C-S and 2C-H). Table 3 shows the search strategy after finding a feasible solution of the mBSSRP. In Table 3, the first search method 2A-S involves to searching for all neighborhood solutions of the Or-opt and the CROSS-exchange with soft constraints. The second search method 2A-H involves searching for all neighborhood solutions of the Or-opt and the CROSS-exchange with hard constraints. The difference between the search methods 2A-S and 2A-H is whether the instances are solved with hard or soft constraints. The reason why we introduced both soft and hard constraints is that we found that once a feasible solution of the mBSSRP is obtained, our conventional method [20] searches for the feasible solutions successively. Then, 2A-S and 2A-H are the same as the conventional search method [20]. The third search method 2B-S only searches for insertion in the normal order of the Or-opt with soft constraints. The fourth search method 2B-H only searches for insertion in the normal order of the Or-opt with hard constraints. The fifth search method 2C-S explores the insertion of the normal order of the Or-opt and the exchange of the normal order of the CROSS-exchange with soft constraints. Finally, the sixth search method 2C-H explores the insertion of the normal order of the Or-opt and the exchange of the normal order of the CROSS-exchange with hard constraints.

Table 2. Search strategy before finding a feasible solution of the mBSSRP. The first column shows local search names, the second column shows the types of the Or-opt or the CROSS-exchange operations, the third to fifth columns show the name of the search method and the sixth column shows the percentage of local search methods that are executed.

Local Search	Type	1A-S	1B-S	1C-S	Executed Rate (One Decimal Point Omitted)
Or-opt	Normal	✓	✓	✓	66%
	Reverse	✓			4%
CROSS-exchange	Normal	✓		✓	20%
	One-sided reverse	✓			2%
	One-sided reverse	✓			3%
	Reverse	✓			4%
	Reverse				

Table 3. Search strategy after finding a feasible solution of the mBSSRP. The first column represents local search names, the second column shows the types of the Or-opt or the CROSS-exchange operations, the third to the eighth columns show the name of the search method and the bottom line indicates whether instances were solved with hard or soft constraints.

Local Search	Type	2A-S	2A-H	2B-S	2B-H	2C-S	2C-H
Or-opt	Normal	✓	✓	✓	✓	✓	✓
	Reverse	✓	✓				
CROSS-exchange	Normal	✓	✓			✓	✓
	One-sided reverse	✓	✓				
	One-sided reverse	✓	✓				
	Reverse	✓	✓				
	One-sided reverse						
	Reverse						
Constraint		Soft	Hard	Soft	Hard	Soft	Hard

5. Numerical Experiments

To evaluate the performance of the computational cost reduction methods, we generated benchmark instances. Figure 7 shows an example of these instances. We distributed 100 ports and a depot uniformly in a region measuring 10 km². The number of bicycles at each port was set to a random number between −5 and +5 at intervals of 1. A negative value (−) represents the delivery port, and a positive value (+) represents the pickup ports. The capacity of the vehicles was 10, the average moving speed of the vehicles was 30 [km/h], the loading or unloading time of a bicycle was 2 [min] and the time limit (all vehicles start from the depot and return to it) was 180 [min]. Thereafter, the tabu tenure was set to 50 and the initial values of weights were set to $\alpha(0) = 1$ and $\beta(0) = 1$. The increasing λ and decreasing parameter μ were set to 1.07 and 0.3, respectively.

For the search methods 1A-S, 1B-S and 1C-S (before a feasible solution was obtained), we performed 50 trials per instance and performed 200 [s] of computation for trials. Meanwhile, for the search methods 2A-S, 2A-H, 2B-S, 2B-H, 2C-S and 2C-H (after a feasible solution was obtained), we started the calculation from 50 feasible solutions per instance and performed 200 [s] of computation for each solution. These numerical experiments were performed on a Mac mini with a 3-GHz 6-Core Intel Core i5 processor and 32 GB RAM.

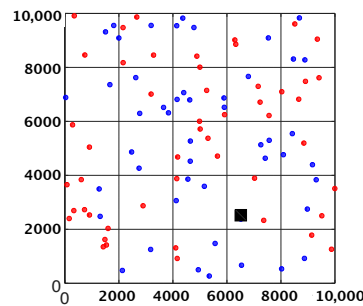


Figure 7. An example of instance. A black square represents a depot, red circles represent pickup ports and blue circles represent delivery ports.

5.1. Results of Search Strategy before Obtaining a Feasible Solution

Results of the numerical experiments for the search strategy before obtaining a feasible solution are shown in Table 4. In Table 4a–c, the first column lists the instance numbers, the second to the fourth columns present the average, the best and the worst objective function values [min] for each instance, and the fifth column indicates the number of obtained feasible solutions for each trial. We performed 50 trials; thus, the maximum value was 50. Table 4a summarizes the result that searches for all neighborhood solutions of the Or-opt and the CROSS-exchange (the search method 1A-S). From Table 4a, feasible solutions of the mBSSRP were obtained for almost all trials. From Table 4b, the search method that searches for only normal order of the Or-opt (the search method 1B-S) cannot obtain several feasible solutions compared to Table 4a. By contrast, the search method 1C-S (Table 4c) obtained almost the same number of feasible solutions and the average objective function values [min] as the search method 1A-S (Table 4a).

To compare the performance of the search methods 1A-S and 1C-S by statistical analysis, we used the *t*-test. Table 5 shows the results of the *t*-test. In Table 5, the first column lists the instance numbers, the second and the fourth columns present the average objective function values [min] for each instance, the third and the fifth columns show the standard deviations and the sixth column presents the results of the *t*-test. In the numerical experiment, the level of significance was 5%. Thus, if $p \geq 0.05$, there is no significant difference between the performance of the search methods 1A-S and 1C-S. By contrast, if the results show that $p < 0.05$, there is a significant difference between the performance of the search methods 1A-S and 1C-S. From Table 5, only for instance No.1 and No.10, the *p*-values are smaller than 0.05. However, for instance No.2~No.9 (Table 5), the *p*-values are larger than 0.05. These results indicate that we cannot say that there is a significant difference between the performance of the search methods 1A-S and 1C-S.

Next, to clarify the difference between the search methods 1A-S and 1C-S, we evaluated the relationship between the time [s] until a feasible solution was obtained and the number of obtained feasible solutions (Figure 8). Figure 8a shows the result of the search method 1A-S (search for all neighborhood solutions of the Or-opt and the CROSS-exchange), and Figure 8b shows the result of the search method 1C-S (search for normal order insertion of the Or-opt and normal order exchange of the CROSS-exchange). The horizontal axis shows time [s] and the vertical axis indicates the number of obtained feasible solutions. We can see that the highest value of the number of obtained feasible solutions takes approximately 70 [s] from Figure 8a. Meanwhile, the highest value of the number of obtained feasible solutions takes approximately 40 [s] from Figure 8b. Thus, although the number of obtained feasible solutions and the average objective function values [min] for the search methods 1A-S and 1C-S were almost the same as shown in Table 4, the search method 1C-S finds a feasible solution approximately 30 [s] faster than the search method 1A-S (Figure 8).

To investigate whether there is a significant difference in the average time [s] until a feasible solution was obtained between the search methods 1A-S and 1C-S, we also

conducted a statistical analysis by the t -test. Table 6 shows the results of the t -test. In Table 6, the first column lists the instance numbers, the second and the fourth columns present the average time [s] until a feasible solution was obtained for each instance, the third and the fifth columns show the standard deviations and the sixth column presents the results of the t -test. From the results, the p -values are smaller than 0.05 except for instance No.6. Thus, we could find a significant difference between the search methods 1A-S and 1C-S for almost all instances from the viewpoint of a searching speed.

Table 4. Results of search methods before obtaining a feasible solution. (a) Search method 1A-S (search for all neighborhood solutions of the Or-opt and the CROSS-exchange). (b) Search method 1B-S (search only normal order insertion of the Or-opt). (c) Search method 1C-S (search for normal order insertion of the Or-opt and normal order exchange of the CROSS-exchange).

(a)				
No.	Avg. [min]	Best [min]	Worst [min]	# of Feasible Solution
1	243.76	230.85	259.07	50
2	238.16	230.87	252.95	50
3	228.47	218.98	237.25	50
4	242.56	232.38	252.36	50
5	249.06	240.95	260.69	50
6	270.81	260.50	284.04	31
7	238.52	225.12	252.72	34
8	213.15	207.43	226.01	50
9	241.64	231.13	255.18	49
10	243.28	234.40	252.54	45
Avg.	240.94	231.26	253.28	45.9
(b)				
No.	Avg. [min]	Best [min]	Worst [min]	# of Feasible Solution
1	245.46	234.80	258.63	40
2	242.59	228.66	260.92	50
3	234.57	222.44	249.94	50
4	246.81	236.23	268.79	49
5	254.91	241.88	269.26	42
6	268.45	260.94	276.57	16
7	238.02	222.71	247.85	10
8	213.98	207.79	237.93	49
9	245.18	233.40	260.38	44
10	244.20	236.92	257.74	29
Avg.	243.42	232.58	258.80	37.9
(c)				
No.	Avg. [min]	Best [min]	Worst [min]	# of Feasible Solution
1	241.63	233.74	251.90	50
2	236.61	227.33	246.43	50
3	228.31	217.29	242.36	50
4	242.15	233.15	254.30	50
5	249.59	241.04	259.27	50
6	269.55	256.99	284.94	32
7	236.17	225.00	252.39	30
8	213.14	205.85	224.93	50
9	239.44	228.72	252.01	50
10	239.80	229.91	253.65	44
Avg.	239.64	229.90	252.22	45.6

To summarize the results, there is no difference in the performance between the search methods 1A-S and 1C-S (Tables 4 and 5). On the other hand, as for the search speed, the search method 1C-S (54.53 [s]) can find feasible solutions with shorter time (approximately 30 [s]) than the search method 1A-S (85.29 [s]), which means that by using the search method 1C-S, we can reduce the computation time by $(85.29 - 54.53) / 85.29 \times 100 = 36.1\%$. Therefore, we concluded that the search method 1C-S (the search for the normal order insertion of the Or-opt and the normal order exchange of the CROSS-exchange) is the best search method before finding a feasible solution.

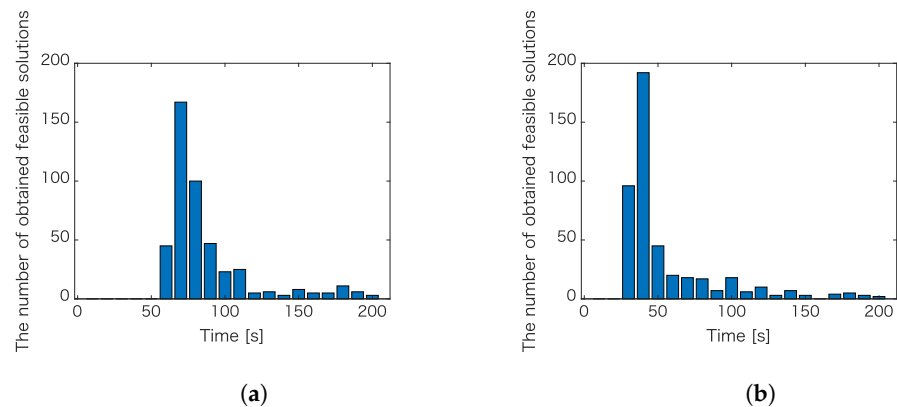


Figure 8. Relationship between time until a feasible solution is firstly obtained and the number of obtained feasible solutions. (a) Search method 1A-S (search for all neighborhood solutions of the Or-opt and the CROSS-exchange). (b) Search method 1C-S (search for normal order insertion of the Or-opt and normal order exchange of the CROSS-exchange).

Table 5. Results of the *t*-test to evaluate the difference of the average objective function values [min] between the search methods 1A-S and 1C-S.

No.	1A-S		1C-S		<i>p</i>
	Avg. [min]	SD	Avg. [min]	SD	
1	243.76	5.72	241.63	4.51	0.041
2	238.16	5.08	236.61	4.34	0.104
3	228.47	4.36	228.31	6.42	0.886
4	242.56	4.92	242.15	4.54	0.668
5	249.06	4.64	249.59	4.38	0.558
6	270.81	6.42	269.55	7.13	0.464
7	238.52	6.27	236.17	6.96	0.163
8	213.15	3.39	213.14	4.00	0.985
9	241.64	6.19	239.44	5.25	0.061
10	243.28	4.62	239.80	5.14	0.001
Avg.	240.94	5.16	239.64	5.27	0.393

Table 6. Results of the *t*-test to evaluate the difference time [s] until a feasible solution was obtained between the search methods 1A-S and 1C-S.

No.	1A-S		1C-S		<i>p</i>
	Avg. [s]	SD	Avg. [s]	SD	
1	78.76	24.84	44.67	16.83	0.000
2	72.83	16.30	32.84	5.60	0.000
3	66.37	10.68	30.22	5.79	0.000
4	75.37	13.50	36.85	9.72	0.000
5	72.86	10.15	42.23	15.70	0.000
6	123.70	41.62	109.59	45.82	0.205
7	115.36	37.28	89.80	45.26	0.018
8	68.81	19.88	32.74	8.61	0.000
9	75.99	16.51	42.16	16.41	0.000
10	102.82	39.51	84.23	42.42	0.035
Avg.	85.29	23.03	54.53	21.22	0026

5.2. Results of Search Strategy after Obtaining a Feasible Solution

Results of the numerical experiments using the six search methods after obtaining the feasible solution are shown in Table 7. In Table 7a–f, the first column lists the instance numbers, the second to the fourth columns present the average, the best and the worst objective function values [min] in 200 [s] of each trial, when we started the calculation from a feasible solution. From Table 7e,f, the search methods of reducing neighborhood solutions were also effective when the search was started from feasible solutions. The performance showed no significant differences between soft (Table 7e) and hard constraints (Table 7f). In particular, the difference of the average objective function values [min] of the search method 2C-S and the search method 2C-H is only 0.39 [min].

To investigate whether there is a significant difference in performance, the *t*-test was used on the average objective function values [min]. Table 8 shows the results of the *t*-test. In Table 8, the first column lists the instance numbers, the second and the fourth columns present the average objective function values [min] for each instance, the third and the fifth columns show the standard deviations, and the sixth column presents the results of the *t*-test. From Table 8, except for instance No.6, the *p*-values are larger than 0.05. Thus, we could not find any significant difference between the performance of the search methods 2C-S and 2C-H from the viewpoint of the statistical analysis.

Next, to investigate whether there is a difference in searching process between the two search methods 2C-S and 2C-H, we evaluated the transition of the most feasible solutions when solving soft and hard constraints. The results of instance No.1 are shown in Figure 9. From Figure 9, we can find that there is a difference between these two search methods 2C-S and 2C-H. From Figure 9a, it takes a long time (38.82 [s]) to update the better solution for solving the mBSSRP-S. The reason is that to realize an effective search, the weight values of penalty in Equations (3)–(6) must be adjusted to appropriate values. The average transition time to a better solution for other instances is shown in Table 9. In Table 9, the first column lists instance numbers and the second column shows the average transition time [s] to a better solution. From Table 9, the search method 2C-S takes about 30~80 [s] to find a better feasible solution. Meanwhile, from Figure 9b, a solution of the search method 2C-H moves to a better solution as soon as a search is started because it cannot search for an infeasible solution.

The results of the *t*-test of the average objective function values of the search methods 2C-S and 2C-H showed that there was no significant difference in performance (Tables 7 and 8). However, from Figure 9 and Table 9, the search method 2C-H can find a better feasible solution in a shorter time (approximately 30~80 [s]) than the search method 2C-S. Therefore, as for the search strategy after finding a feasible solution, we concluded that the search method 2C-H (the search for the normal order insertion of the Or-opt

and the normal order exchange of the CROSS-exchange with hard constraints) is the best search method.

Table 7. Results of search methods after obtaining a feasible solution. (a) Search method 2A-S (search for all neighborhood solutions of the Or-opt and the CROSS-exchange with soft constraints). (b) Search method 2A-H (search for all neighborhood solutions of the Or-opt and the CROSS-exchange with hard constraints). (c) Search method 2B-S (search for only normal order insertion of the Or-opt with soft constraints). (d) Search method 2B-H (search for only normal order insertion of the Or-opt with hard constraints). (e) Search method 2C-S (search for normal order insertion of the Or-opt and normal order exchange of the CROSS-exchange with soft constraints). (f) Search method 2C-H (search for normal order insertion of the Or-opt and normal order exchange of the CROSS-exchange with hard constraints).

(a)			
No.	Avg. [min]	Best [min]	Worst [min]
1	241.81	232.13	254.94
2	238.45	227.14	245.73
3	228.09	218.60	244.40
4	241.43	231.95	251.71
5	247.58	240.39	256.60
6	266.76	257.19	281.07
7	234.84	222.53	251.80
8	212.02	205.77	220.14
9	240.48	232.09	251.94
10	241.65	230.99	256.75
Avg.	239.31	229.88	251.51

(b)			
No.	Avg. [min]	Best [min]	Worst [min]
1	242.53	235.06	251.29
2	237.70	229.25	247.47
3	227.98	219.98	237.32
4	241.36	231.52	250.18
5	248.68	241.96	258.93
6	268.91	253.71	286.59
7	235.25	222.83	255.66
8	211.91	205.99	218.02
9	239.90	227.68	253.67
10	239.90	231.80	252.12
Avg.	239.41	229.98	251.13

(c)			
No.	Avg. [min]	Best [min]	Worst [min]
1	244.20	232.75	259.46
2	239.29	228.66	249.19
3	227.79	217.16	238.15
4	242.41	234.88	254.57
5	251.11	242.17	264.62
6	270.60	253.39	284.24
7	236.22	226.03	251.93
8	211.75	206.02	223.83
9	243.22	231.37	258.92
10	241.93	230.33	258.83
Avg.	240.85	230.28	254.37

Table 7. Cont.

(d)			
No.	Avg. [min]	Best [min]	Worst [min]
1	248.89	236.91	270.39
2	241.65	228.40	258.26
3	230.96	221.46	244.89
4	246.12	230.94	263.21
5	252.34	240.32	267.20
6	275.42	263.31	286.62
7	242.98	225.28	262.27
8	212.27	206.68	222.78
9	243.85	233.61	259.85
10	249.20	231.04	266.57
Avg.	244.37	231.79	260.20
(e)			
No.	Avg. [min]	Best [min]	Worst [min]
1	240.88	232.42	254.18
2	235.86	228.96	243.84
3	226.88	216.81	235.18
4	240.18	231.96	254.29
5	246.75	241.68	254.52
6	264.58	255.89	276.92
7	234.09	222.51	254.30
8	211.11	205.87	216.95
9	237.62	227.48	249.52
10	238.92	230.84	249.83
Avg.	237.69	229.44	248.95
(f)			
No.	Avg. [min]	Best [min]	Worst [min]
1	241.36	232.87	255.56
2	236.58	227.65	249.19
3	225.96	216.81	233.52
4	239.99	231.78	247.36
5	247.18	240.11	255.19
6	267.60	254.18	281.03
7	235.12	222.29	255.66
8	210.42	206.12	215.98
9	238.72	230.49	247.28
10	237.86	230.42	253.19
Avg.	238.08	229.27	249.40

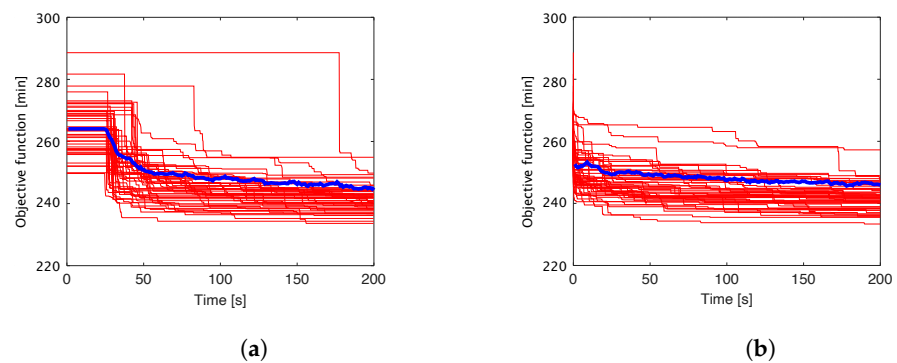


Figure 9. Transition of the best solutions found in case of instance No.1. The red lines show the transition of the best feasible solution from 50 initial feasible solutions, whereas the blue lines show their average. (a) Search method 2C-S (search for normal order insertion of the Or-opt and normal order exchange of the CROSS-exchange with soft constraints). (b) Search method 2C-H (search for normal order insertion of the Or-opt and normal order exchange of the CROSS-exchange with hard constraints).

Table 8. Results of the *t*-test to evaluate the difference of performance between methods 2C-S and 2C-H.

No.	2C-S		2C-H		<i>p</i>
	Avg. [min]	SD	Avg. [min]	SD	
1	240.88	4.20	241.36	4.41	0.572
2	235.86	3.89	236.58	5.18	0.432
3	226.88	4.64	225.96	4.39	0.309
4	240.18	4.74	239.99	3.66	0.833
5	246.75	3.26	247.18	3.92	0.550
6	264.58	5.27	267.60	6.45	0.016
7	234.09	7.27	235.12	8.14	0.518
8	211.11	2.86	210.42	2.54	0.209
9	237.62	5.09	238.72	4.64	0.262
10	238.92	3.91	237.86	4.27	0.203
Avg.	237.69	4.51	238.08	4.76	0.390

Table 9. Results of the average transition time to a feasible solution for the search method 2C-S.

No.	Avg. [s]
1	38.82
2	31.54
3	31.71
4	36.01
5	34.17
6	77.78
7	68.04
8	29.10
9	35.56
10	59.94
Avg.	44.27

6. Conclusions

In this study, we proposed two search strategies with low computational costs while maintaining the performance of the mBSSRP: the first one is to reduce neighborhood solutions to obtain a feasible solution in a short time before finding a feasible solution

of the mBSSRP, and the second one is to change the problem to be solved (mBSSRP or mBSSRP-S) after a feasible solution is obtained and to search good near-optimal solutions in a short time.

As the first search strategy before obtaining a feasible solution, we propose two search methods (the search methods 1B-S and 1C-S) and compare their performance with our previous method (the search method 1A-S) [20]. The search method 1A-S searches for all neighborhood solutions of the Or-opt and the CROSS-exchange [20]. The search method 1B-S searches only the normal order insertion of the Or-opt. The search method 1C-S searches for the normal order insertion of the Or-opt and the normal order exchange of the CROSS-exchange. The results of the numerical experiments showed that the search method 1C-S that only searches for the normal order insertion of the Or-opt and the normal order exchange of the CROSS-exchange is the best search method, because the search method 1C-S obtained many feasible solutions within a short time.

Next, as the second search strategy after a feasible solution of mBSSRP is obtained, we propose four search methods (2B-S, 2B-H, 2C-S and 2C-H) and compare their performance with our previous methods (2A-S and 2A-H) [20]. The search method 2A-S searches for all neighborhood solutions of the Or-opt and the CROSS-exchange with soft constraints. The search method 2A-H searches for all neighborhood solutions of the Or-opt and the CROSS-exchange with hard constraints. The search method 2B-S searches for insertion in the normal order of the Or-opt with soft constraints. The search method 2B-H searches for insertion in the normal order of the Or-opt with hard constraints. The search method 2C-S searches for the insertion of the normal order of the Or-opt and the exchange of the normal order of the CROSS-exchange with soft constraints. Finally, the search method 2C-H searches for the insertion of the normal order of the Or-opt and the exchange of the normal order of the CROSS-exchange with hard constraints. The results of the numerical experiments showed that the search method 2C-H that searches for the normal order insertion of the Or-opt and the normal order exchange of the CROSS-exchange with hard constraints is the best search method, because the search method 2C-H obtained short tours within a short time. These results indicate that the search method 1C-S reduces the neighborhood solutions in the Or-opt and the CROSS-exchange and that the search space was shifted from soft constraints to hard constraints after a feasible solution is obtained is effective.

In this study, we used a dynamically changing method for weight parameters (α and β) to find good solutions of mBSSRP from the solution of the mBSSRP-S. To adjust these weight parameters α and β , we used an adjustment method (Equations (3)–(6)). Then, from the results of numerical experiments (Figure 9a), it takes a long time to update the better solution for solving the mBSSRP-S (for example, 38.82 [s] for instance No. 1). The results of other instances are shown in Table 9. From Table 9, the search method 2C-S takes about 30~80 [s] to find better feasible solutions. In this temporal duration of 30~80 [s], the weight values α and β must be adjusted to appropriate values by Equations (3)–(6). If we can set optimal parameters for an initial state, the search method 2C-S can find a better solution more efficiently and quickly than the search method 2C-H. Thus, one of the future works is to determine the parameters by using a parameter optimization approach.

In the numerical experiment, we used randomly distributed ports. However, some bicycle sharing repositioning studies have used real BSS data. For instance, Rainer-Harbach et al. (2013) [13], Raidl et al. (2013) [14] and Papazek et al. (2013) [15] use data from Vienna, and Chiariotti et al. (2018) [17] use data from New York. Thus, it is an important work to use real BSS data in a future study.

Moreover, we need to address the dynamic cases because the number of bicycles in each port changes while restoring bicycles in the real BSS. The studies of static BSS (Rainer-Harbach et al. (2013) [13], Raidl et al. (2013) [14] and Papazek et al. (2013) [15]) have been extended to dynamic BSS by Kloimüller et al. (2014) [16]. Thus, we also aim to extend this study to a dynamic case. The completion of the dynamic case would have a great impact on solving an issue inherent in BSS: users cannot rent or return a bicycle at an empty or a

full port. A solution to this issue would lead to the development of BSS in the future, and it is expected that BSS will be used for a wide range of purposes such as commuting to work, daily life, and even in times of disaster. It will also have an effect to promote the spread of the next generation system called MaaS (Mobility as a Service), which has been attracting attention recently: all public transportation systems are connected by IT technology. To address the dynamic case, we have to consider forecasting future demands of bicycles from actual data and repositioning them based on the forecast data by investigating statistical characteristics of real data of BSSs [32].

In our previous study [20], we proposed a heuristic method by using the tabu search. Then, in this paper, we also used the tabu search to propose search strategies with low computational costs while maintaining the performance of the mBSSRP. However, it is important to use not only the tabu search but also the other approaches (for example, simulated annealing) and compare these approaches. In addition, we only focus on the operation of the rebalancing bicycles [19,20] and statistical analysis of BSS usage history [32]. However, Kabak et al. (2018) [33] focus on the location of bicycle ports. It is an important idea to evaluate the existing BSS ports and suggest alternative places for additional BSS ports.

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References

- DeMaio, P.; Meddin, R. The Bike-Sharing World Map. Available online: <https://bikesharingworldmap.com/#/acoruna/> (accessed on 17 February 2021).
- BIXI Official Site. Available online: <https://bixi.com> (accessed on 17 February 2021).
- Velib' Official Site. Available online: <https://www.velib-metropole.fr> (accessed on 17 February 2021).
- Docomo Bike Share Official Site. Available online: <https://docomo-cycle.jp/> (accessed on 17 February 2021).
- Citybike Official Site. Available online: <https://www.citybikewien.at/de/> (accessed on 17 February 2021).
- Citi Bike Official Site. Available online: <https://www.citibikenyc.com/> (accessed on 17 February 2021).
- Capital Bikeshare Official Site. Available online: <https://www.capitalbikeshare.com> (accessed on 17 February 2021).
- BULEbikes Official Site. Available online: <https://www.bluebikes.com> (accessed on 17 February 2021).
- Bicing Official Site. Available online: <https://www.bicing.barcelona> (accessed on 17 February 2021).
- Zhang, Y.; Mi, Z. Environmental benefits of bike sharing: A big data-based analysis, *Appl. Energy* **2018**, *220*, 296–301.
- Dell'Amico, M.; Hadjicostantinou, E.; Iori, M.; Novellani, S. The bike sharing rebalancing problem: Mathematical formulations and benchmark instances. *Omega* **2014**, *45*, 7–19.
- Dell M.; Iori, M.; Novellani, S.; Stützle, T. A destroy and repair algorithm for the bike sharing rebalancing problem. *Comput. Oper. Res.* **2016**, *71*, 149–162.
- Rainer-Harbach, M.; Papazek, P.; Hu, B.; Raidl, G.R. Balancing bicycle sharing systems: A variable neighborhood search approach. In *Evolutionary Computation in Combinatorial Optimisation—13th European Conference, EvoCOP 2013*; Middendorf, M.; Blum, C. Eds.; Lecture Notes in Computer Science; Springer: Berlin/Heidelberg, Germany, 2013; Volume 7832, pp. 121–132.
- Raidl, G.R.; Hu, B.; Rainer-Harbach, M.; Papazek, P. Balancing bicycle sharing systems: Improving a VNS by efficiently determining optimal loading operations. In *Hybrid Metaheuristics, 8th International Workshop, HM 2013*; Blesa, M.J., Blum, C., Festa, P., Roli, A., Sampels, M., Eds.; Lecture Notes in Computer Science; Springer: Berlin/Heidelberg, Germany, 2013; Volume 7919, pp. 130–143.
- Papazek, P.; Raidl, G.R.; Rainer-Harbach, M.; Hu, B. A PILOT/VND/GRASP hybrid for the static balancing of public bicycle sharing systems. In *Computer Aided Systems Theory—EUROCAST 2013*; Moreno-Díaz, R., Pichler, F., Quesada-Arencibia, A., Eds.; Lecture Notes in Computer Science; Springer: Berlin/Heidelberg, Germany, 2013; Volume 8111, pp. 372–379.

16. Kloimüller, C.; Papazek, P.; Hu, B.; Raidl, G.R. Balancing bicycle sharing systems: An approach for the dynamic case. In *Evolutionary Computation in Combinatorial Optimization—EvoCOP 2014*; Blum, C., Ochoa, G., Eds.; Lecture Notes in Computer Science; Springer: Berlin/Heidelberg, Germany, 2014; Volume 8600, pp. 73–84.
17. Chiariotti, F.; Pielli, C.; Zanella, A.; Zorzi, M. A dynamic approach to rebalancing bike-sharing systems. *Sensors* **2018**, *18*, 512.
18. Gurobi Optimizer. Available online: <http://www.gurobi.com> (accessed on 17 February 2021).
19. Tsushima, H.; Matsuura, T.; Jin'no, K. Local search method for multiple-vehicle bike sharing system routing problem. *J. Signal Process.* **2018**, *22*, 157–160.
20. Tsushima, H.; Matsuura, T.; Ikeguchi, T. Strategy for Exploring Feasible and Infeasible Solution Spaces to Solve a Multiple-Vehicle Bike Sharing System Routing Problem. *Appl. Sci.* **2021**, *11*, 7749.
21. Or, I. Traveling salesman-type combinatorial problems and their relation to the logistics of blood banking. Ph.D. Thesis, Department of Industrial Engineering and Management Science, Northwestern University, Evanston, IL, USA, 1976.
22. Taillard, É.; Badeau, P.; Gendreau, M.; Guertin, F.; Potvin, J.Y. A tabu search heuristic for the vehicle routing problem with soft time windows. *Transp. Sci.* **1997**, *31*, 170–186.
23. Glover, F. Tabu search-part I. *ORSA J. Comput.* **1989**, *1*, 190–206.
24. Glover, F. Tabu search-part II. *ORSA J. Comput.* **1990**, *2*, 4–32.
25. Glover, F.; Taillard, E. A user's guide to tabu search. *Ann. Oper. Res.* **1993**, *41*, 3–28.
26. Hasegawa, M.; Ikeguchi, T.; Aihara, K. Solving large scale traveling salesman problems by chaotic neurodynamics. *Neural Netw.* **2002**, *15*, 271–283.
27. Matsuura, T.; Ikeguchi, T. Chaotic search for traveling salesman problems by using 2-opt and Or-opt algorithms. In *Artificial Neural Networks—ICANN 2008*; Lecture Notes in Computer Science; Springer: Berlin/Heidelberg, Germany, 2008; Volume 5164.
28. Motohashi, S.; Matsuura, T.; Ikeguchi, T. Chaotic search method using the Lin-Kernighan algorithm for traveling salesman problems. In *Proceedings of International Symposium on Nonlinear Theory and its Applications 2008*, Budapest, Hungary, 7–10 September 2008; pp. 144–147.
29. Motohashi, S.; Matsuura, T.; Ikeguchi, T.; Aihara, K. The Lin-Kernighan algorithm driven by chaotic neurodynamics for large scale traveling salesman problems. In *Artificial Neural Networks—ICANN 2009*; Lecture Notes in Computer Science; Springer: Berlin/Heidelberg, Germany, 2009; Volume 5769.
30. Taillard, É.; D.; Helsgaun, K. POPMUSIC for the travelling salesman problem, *Eur. J. Oper. Res.* **2019**, *272*, 420–429.
31. Aritra, A.; Zhang, Y. Free-floating bike sharing: Solving real-life large-scale static rebalancing problems. *Transp. Res. Part Emerg. Technol.* **2017**, *80*, 92–116.
32. Tsushima, H.; Ikeguchi, T. Statistical analysis of usage history of bicycle sharing systems. *Nonlinear Theory Its Appl. IEICE* **2021**, *E13-N*, 2.
33. Kabak, M.; Erbaş, M.; Cetinkaya, C.; Özceylan, E. A GIS-based MCDM approach for the evaluation of bike-share stations. *J. Clean. Prod.* **2018**, *201*, 49–60.

Article

Strategy for Exploring Feasible and Infeasible Solution Spaces to Solve a Multiple-Vehicle Bike Sharing System Routing Problem

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Abstract: In bicycle sharing systems, many vehicles restore bicycles to ports. To construct the shortest tour of these vehicles, in a previous work, we formulated the multiple-vehicle bike sharing system routing problem (mBSSRP) and demonstrated that an optimal solution can be obtained for small-sized instances through a general-purpose mixed-integer linear programming solver. However, for large-sized instances, the optimal solution could not be found in a reasonable time frame. Therefore, to find near-optimal solutions for the mBSSRPs in a short time, in this study, we develop a method with a searching strategy, which explores both the feasible and infeasible solution spaces. To investigate the performance of the proposed method, we solve benchmark problems of mBSSRP. In addition, we compare the proposed method with the method exploring only the feasible solution space, in terms of performance. The results of the numerical experiments demonstrate that the proposed method can reach optimal solutions for almost all small-sized mBSSRP instances and that searching both the feasible and infeasible solution spaces yields good feasible solutions both for small-sized and large-sized instances.

Keywords: bicycle sharing system; heuristic method; tabu search; feasible and infeasible solution

1. Introduction

In recent years, bicycle sharing systems (BSSs) have been implemented in many cities around the world to ease traffic jams in town centers, to reduce CO₂ emissions and to improve public health [1]. A BSS is composed of many dispersed automatic rental ports with rental bicycles. People can rent a bicycle at one of the many ports and return it to a different port. In BSSs, when many bicycles are used, the number of bicycles at each port becomes unbalanced, because almost all users conduct not only round trips but also one-way trips. To overcome this problem, capacitated vehicles restore the required number of bicycles to the rental ports.

Recently, many researchers have investigated the optimum rebalancing of the bicycles with BSSs. Chemla et al. (2013) [2] proposed a branch-and-cut-algorithm for finding an optimal solution to the static rebalancing problem using a single vehicle with up to 100 ports. The results of their numerical experiments demonstrated that their method is very efficient up to 60 ports [2]. Wada et al. (2013) [3] proposed a construction method and a local search method for the bike sharing system routing problem. They reported that for up to 50 ports, their proposed method performed better than their previous method [3].

In real-life situations, the number of ports is more than 100, making it almost impossible to restore the bicycles using a single vehicle. To address this issue, a bike repositioning problem with multiple vehicles has been proposed [4–6]. Lin et al. (2012) [4] proposed heuristic algorithms using the actual path distance and a maximum of 11 vehicles to demonstrate that shorter travel distances are obtained when the actual path distance is used instead of the Euclidean distance [4]. Raviv et al. (2013) [5] presented two mixed-integer linear program formulations, with the aim of minimizing the total travel cost and penalty cost. They obtained good solutions for the Paris and Washington D.C. problems, using two vehicles, with an instance size up to 60 ports and 104 ports, respectively [5]. Ho et al. (2017) [6] proposed a hybrid large neighborhood search method and tested instances with up to 518 ports using a maximum of three vehicles. They conducted experiments and compared their solution with the method proposed by Forma et al. (2015) [7] and they obtained better solutions than Forma et al. (2015) [7]. In Refs. [4–6], it is assumed that the vehicles do not need to visit all ports. In this case, an operator cannot notice a broken bicycle or any trouble at the port. To address the problem of visiting all ports using multiple vehicles, Dell’Amico et al. (2014) [8] proposed four mathematical formulations, built a set of benchmark instances and solved them using the branch-and-cut algorithm. An optimal solution was obtained with one of the proposed formulations for the 49 instances out of 65. Research on the bicycle rebalancing problem, while producing interesting results, does not consider time limit constraints [8]. Without a time limit constraint, the operations differ in the amount of work required. In the case of the static bicycle rebalancing problem, the bicycle relocation must be performed within a limited time after the end of the daily BSS. Table 1 summarizes the literature related to the static bicycle rebalancing problem.

Table 1. Summary of the characteristics of the related literature. ✓ indicates that the proposed solution considers visiting all ports or a time limit. ✗ indicates that these are not considered.

Paper	Visit All Ports	Vehicle	Time Limit	Maximum Number of Ports Tested
Lin et al. (2012) [4]	✗	Multiple	✓	132
Chemla et al. (2013) [2]	✗	Single	✗	100
Raviv et al. (2013) [5]	✗	Multiple	✓	104
Wada et al. (2013) [3]	✓	Single	✗	50
Dell’Amico et al. (2014) [8]	✓	Multiple	✗	116
Ho et al. (2017) [6]	✗	Multiple	✓	518

As for other related works, Benchimol et al. (2011) [9] proposed a static bicycle repositioning problem, discussed the complexity of the bicycle relocation process and provided an integer linear programming problem and an approximation algorithm. Schuijbroek et al. (2016) [10] proposed an approach for determining the tours while considering the bicycle demand. It is difficult to directly compare these related studies because of the different constraints that have been considered. This is also mentioned in Kloimüller et al. (2014) [11].

The research on BSS is not only about the relocation of bicycles, but also about the further development of BSS. To expand the BSS, it is necessary to install ports in locations where there is a demand for bicycles. Makarova et al. (2020) [12] proposed port installations and developed a decision support system to automatically calculate the efficiency of the port. They also proposed to assign a new BSS port to improve the safety of the traffic system in Naberezhnye Chelny, Russia. Lyu et al. (2020) [13], in an effort to expand BSS, interviewed the BSS users in Shanghai, China to determine the motivation of BSS users and the factors impeding the development of BSS. As a result of the interviews, it was determined that BSS users are motivated by convenience as well as savings in time and money. However, the drawbacks of using BSS consist of poor bicycle maintenance, mishandling by users and operational problems. Torrisi et al. (2021) [14] conducted a survey targeting university students in Catania and Enna to determine the factors encour-

aging and hindering the use of the bikes. The results of the questionnaire revealed that health management had the highest weight among encouraging factors, while the lack of infrastructure and safe cycle routes had the highest weight among hindering factors. Cheng et al. (2021) [15] investigated the effect of public transportation closures on BSS demand in Washington D.C. It was determined that, in the case of public transportation closures, BSS is used as supplementary transportation, and the frequency of bicycle use depends on the proximity of the ports to metro stations. They also showed that extreme weather prevented the use of bicycles.

In our previous study, we formulated a new bike sharing system routing problem, called the “multiple-vehicle bike sharing system routing problem” (mBSSRP) [16]. In mBSSRP, multiple vehicles visit all ports only once within a time limit. We then confirmed that an optimal solution could be obtained by using a mixed-integer linear programming (MIP) solver for small-sized instances [16,17]. For large-sized instances, however, the optimal solution could not be found within a reasonable time frame. We have already proposed construction and local search methods for mBSSRP [18]. Through numerical experiments, we confirmed that the proposed method constructs short tours in a short time. However, the construction method used in Ref. [18] cannot provide feasible solutions for some benchmark instances due to the strict constraints of the mBSSRP. Thus, a method that can provide feasible solutions for any instances is required.

In real-life problems, a solution is required even when all constraints are not satisfied. For example, an operation that could be completed in a few minutes will still be carried out beyond the time limit. To address such cases, we formulated a new bike sharing system routing problem called the “multiple-vehicle bike sharing system routing problem with soft constraints” (mBSSRP-S). In the mBSSRP-S, some constraints of the mBSSRP are removed, while adding weighted penalties to the objective function for the violations corresponding to these constraints. Thus, the solution space of mBSSRP is explored such that if the penalty value of an mBSSRP-S solution is zero, the solution is feasible; however, if the penalty value is greater than zero, the solution is infeasible. By solving the mBSSRP-S, we can explore the feasible and infeasible solution spaces of the mBSSRP.

The aim of solving the mBSSRP-S is to obtain feasible solutions. To this end, we propose a meta-heuristic method that explores the feasible and infeasible solution spaces. The proposed method consists of three steps. First, an initial solution is constructed. Next, the initial solution is improved by the local search methods. However, the local search methods cannot find the optimal solution when they are trapped in local minima. To avoid local minima, or to jump out of a local minimum in the search space, several meta-heuristics are proposed, such as genetic algorithms [19], simulated annealing [20], neural networks [21–23] and the tabu search [24,25]. In this study, we used the tabu search to find better solutions for mBSSRP [24,25]. The tabu search is one of the most powerful meta-heuristic methods and has proved effective in solving many combinatorial optimization problems, such as the traveling salesman problem [26], quadratic assignment problem [27] and vehicle routing problem [28].

Moreover, to search the feasible and infeasible solution spaces effectively, we propose a weight adjusting method that dynamically adjusts the penalty weights in accordance with an obtained solution. We investigate the effectiveness of the proposed method for solving the mBSSRP. The results of the numerical experiments demonstrate that searching both the feasible and infeasible solution spaces yields a feasible solution for all instances and is effective in solving problems with strict constraints.

2. Problem Formulation

In this section, we present two types of mBSSRP formulations. In the first problem, there are strict constraints regarding the time limit and the number of bicycles that the vehicles can restore to each port. The first problem is referred to as mBSSRP. In the second problem, some constraints of the first problem are removed and the violations of these

constraints are added to the objective function of the first problem as penalties. The second problem is referred to as mBSSRP-S.

2.1. Multiple-Vehicle Bike Sharing System Routing Problem

In this section, an integer linear programming formulation of mBSSRP is described. The mBSSRP consists of a depot and many ports where rental bicycles are parked. The ports are classified into two sets: (i) a set of delivery ports with a shortage of rental bicycles and (ii) a set of pickup ports. From the pickup ports, some bicycles are transported to the delivery ports because of inadequate bicycle parking space. In mBSSRP, multiple vehicles transport the bicycles from the pickup port to the delivery port. All vehicles start from the depot, load and unload bicycles at the corresponding ports and return to the depot. The vehicles can leave the depot loaded with bicycles because there are many bicycles at the depot. The tour of the vehicles must satisfy the following constraints:

- Time limit constraint
All vehicles must start at the depot and return to the depot within a limited time.
- Capacity constraint
The number of bicycles loaded onto the vehicle cannot exceed its capacity throughout the tour.
- Visiting constraint
Each port must be visited exactly once by a vehicle.
- Loading and supplying constraint
The vehicle must load all excess bicycles and supply the required bicycles in one visit.

Under the above constraints, the goal of the mBSSRP is to find tours that minimize the total travel time of all vehicles.

Let $G = (V, E)$ be a graph, where $V = \{0, 1, \dots, n\}$ is a set of nodes representing a depot $\{0\}$ and ports $\{1, \dots, n\}$, and E is a set of edges. Let t_{ij} be the travel time from port i to port j ($t_{ij} = t_{ji}$). Let b_i be the number of excess or shortage bicycles at port i . If $b_i > 0$, b_i bicycles are in excess at port i . In this case, b_i bicycles at port i are transported to the delivery ports. If $b_i < 0$, the vehicle must supply b_i bicycles to port i . In mBSSRP, the excess bicycles are delivered to the delivery ports by multiple vehicles. The set of capacitated vehicles is $K = \{1, \dots, m\}$. The vehicles cannot carry more than q bicycles. The capacity q is $\max |b_i| \leq q$, because the vehicle can visit each port only once. It takes τ minutes to load/unload one bicycle onto/from the vehicle. The vehicle leaving the depot must restore the bicycles and return to the depot within T minutes.

We introduce four decision variables (Table 2), y_{ik} , x_{ijk} , z_{ijk} and f_{ijk} . The first variable y_{ik} is a 0–1 variable and denotes whether vehicle k visits port i ($y_{ik} = 1$) or not ($y_{ik} = 0$). The second variable x_{ijk} is also a 0–1 variable and denotes whether vehicle k moves from port i to port j directly ($x_{ijk} = 1$) or not ($x_{ijk} = 0$). The third variable z_{ijk} is a non-negative variable that represents the number of bicycles loaded onto vehicle k when vehicle k moves from port i to port j . This third variable z_{ijk} is essential: in the static rebalancing problem, the direction of the vehicle is very important, because the number of bicycles on the vehicle depends on the direction. Let us suppose that five bicycles must be supplied at port 1; two bicycles must be picked up at port 2; and the vehicle is loaded with three bicycles. In this case, the vehicle can travel from port 2 to port 1, but not from port 1 to port 2. This is because, if the vehicle picks up the two bicycles at port 2 before visiting port 1, it cannot supply five bicycles at port 1. Thus, if the decision variable z_{ijk} is not defined, vehicle k cannot determine if it can move from port i to port j . To eliminate sub-tours, the fourth non-negative variable f_{ijk} is used, which represents the number of ports visited by

vehicle k before it reaches port j from port i . Using these four variables, the integer linear programming formulation for the mBSSRP is described as follows:

$$\text{minimize} \quad \sum_{i \in V} \sum_{j \in V} \sum_{k \in K} t_{ij} x_{ijk} \quad (1)$$

$$\text{subject to} \quad \sum_{j \in V \setminus \{0\}} x_{0jk} \leq m \quad \forall k \in K \quad (2)$$

$$\sum_{h \in V \setminus \{0\}} x_{h0k} \leq m \quad \forall k \in K \quad (3)$$

$$\sum_{h \in V} x_{hik} = y_{ik} \quad \forall i \in V \setminus \{0\}, \forall k \in K \quad (4)$$

$$\sum_{j \in V} x_{ijk} = y_{ik} \quad \forall i \in V \setminus \{0\}, \forall k \in K \quad (5)$$

$$\sum_{k \in K} y_{ik} = 1 \quad \forall i \in V \setminus \{0\} \quad (6)$$

$$z_{ijk} \geq 0 \quad \forall i, \forall j \in V, \forall k \in K \quad (7)$$

$$z_{ijk} \leq q x_{ijk} \quad \forall i, \forall j \in V, \forall k \in K \quad (8)$$

$$\sum_{j \in V} z_{ijk} - \sum_{h \in V} z_{hik} = b_i y_{ik} \quad \forall i \in V, \forall k \in K \quad (9)$$

$$\sum_{i \in V} \sum_{j \in V} t_{ij} x_{ijk} + \tau \sum_{i \in V} |b_i| y_{ik} \leq T \quad \forall k \in K \quad (10)$$

$$f_{0jk} = 0 \quad \forall j \in V \setminus \{0\}, \forall k \in K \quad (11)$$

$$\sum_{h \in V \setminus \{0\}} \sum_{k \in K} f_{h0k} = n \quad (12)$$

$$f_{ijk} \leq n x_{ijk} \quad \forall i \in V, \forall j \in V, \forall k \in K \quad (13)$$

$$f_{ijk} \geq 0 \quad \forall i \in V, \forall j \in V, \forall k \in K \quad (14)$$

$$\sum_{j \in V} f_{ijk} - \sum_{h \in V} f_{hik} = y_{ik} \quad \forall i \in V \setminus \{0\}, \forall k \in K \quad (15)$$

$$y_{ik} \in \{0, 1\} \quad \forall i \in V, \forall k \in K \quad (16)$$

$$x_{ijk} \in \{0, 1\} \quad \forall i \in V, \forall j \in V, \forall k \in K \quad (17)$$

Equation (1) is the objective function of the mBSSRP used to minimize the total travel time of all vehicles. Equations (2) and (3) describe that bicycles can be relocated using up to m vehicles, which leave from and return to the depot. Equations (4)–(6) state that every port should be visited exactly once by a vehicle. Equation (7) states that when the vehicle moves from port i to port j , the number of bicycles loaded onto the vehicle is larger than 0, and Equation (8) states that when the vehicle moves from port i to port j , the number of bicycles loaded onto the vehicle is less than the capacity of the vehicle throughout the tour (capacity and loading constraints). Equation (9) states that after visiting port i , the number of bicycles on the vehicle can increase or decrease (supply constraint). Equation (10) describes that all vehicles must return to the depot within the time limit T . Equations (11)–(15) are sub-tour elimination constraints obtained using flow formulation. Finally, Equations (16) and (17) define the variables as binary values. Our formulation of mBSSRP has a time limit constraint and a requirement that all ports are visited, which are not considered in the other BSS study formulations. Thus, all variables are needed.

Table 2. The four decision variables used in the mBSSRP.

y_{ik}	vehicle k visits port i ($y_{ik} = 1$) or not ($y_{ik} = 0$)
x_{ijk}	vehicle k moves from port i to port j directly ($x_{ijk} = 1$) or not ($x_{ijk} = 0$)
z_{ijk}	the number of bicycles loaded onto vehicle k when vehicle k moves from port i to port j
f_{ijk}	the number of ports visited by vehicle k before it reaches port j from port i

2.2. Multiple-Vehicle Bike Sharing System Routing Problem with Soft Constraints

In the mBSSRP, there are three strict constraints, namely the time limit, the capacity and the loading and supplying constraints. As for the time limit constraint, in real life, if a work can be completed through overtime within a few minutes, we would work beyond the time limit. As for the loading and supplying constraints, if we have only four bicycles and are required to supply five bicycles, in real life, we would only supply the four bicycles. In other words, the mBSSRP constraints should not be treated strictly in real-life situations. We propose a problem that treats some of the mBSSRP constraints as penalties. In this problem, violations of these constraints are added to the mBSSRP objective function (Equation (1)). The resulting problem is called mBSSRP-S.

In the mBSSRP-S, the time limit constraint (Equation (10)), the loading and capacity constraints (Equation (8)) and the supplying constraint (Equation (9)) are removed. Instead, the violations of these constraints are added as penalties to obtain the following objective function for the mBSSRP-S.

$$\text{minimize} \quad \sum_{i \in V} \sum_{j \in V} \sum_{k \in K} t_{ij} x_{ijk} + \alpha p_T + \beta (p_{b+} + p_{b-}). \quad (18)$$

In Equation (18), the first term is the sum of the travel times of all vehicles, which is the objective function of mBSSRP. The working time is the sum of the traveling times of the vehicles and the loading and supply times of the bicycles. In Equation (18), α and β are the weights of the penalties for the time limit constraint, and the loading and supplying constraints, respectively; p_T is the excess working time extending beyond T ; p_{b+} refers to the loading and the capacity violation of the bicycles, representing the total number of bicycles that could not be loaded onto the vehicles at the pickup ports; p_{b-} refers to the supplying violation of the bicycles, representing the total number of bicycles that could not be unloaded bicycles to the delivery ports.

Figure 1 shows examples of the violation of the loading and supplying bicycles. In Figure 1, the capacity of the vehicle is five. In Figure 1a,b, the vehicle must load three bicycles at port i (colored in red). In Figure 1a, the vehicle can take all bicycles because the number of bicycles loaded onto the vehicle before visiting port i is two. On the other hand, in Figure 1b, the number of bicycles loaded onto the vehicle is four. Then, the vehicle can load only one bicycle. Therefore, the two bicycles cannot be loaded onto the vehicle. The number of unloaded bicycles is two, and the loading penalty is added to the objective function, namely $p_{b+} = 2$. Figure 1c shows an example of the supplying violation. In Figure 1c, the vehicle must supply three bicycles to port i (colored in blue). However, the number of bicycles loaded onto the vehicle is only one. Therefore, the two bicycles cannot be supplied at port i . The number of unsupplied bicycles is two, and the supplying penalty is added to the objective function, namely $p_{b-} = 2$. When p_T , p_{b+} and p_{b-} are zero, the solution is a feasible mBSSRP solution. However, if one of them is positive, the solution is an infeasible mBSSRP solution.

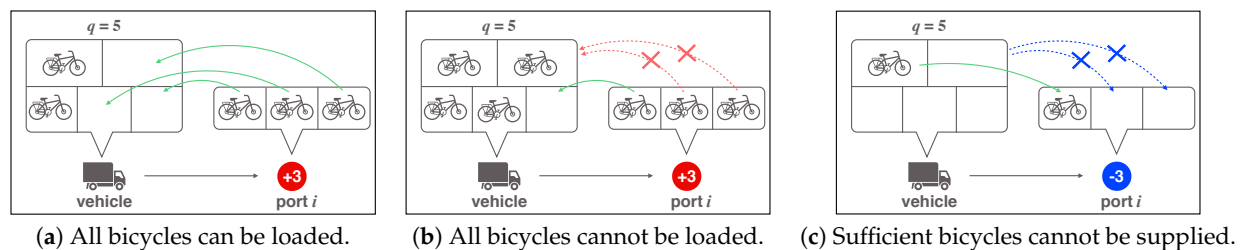


Figure 1. Examples of the loading violation and the supply violation (a–c). In these examples, the capacity of the vehicle is five ($q = 5$). Red and blue circles indicate ports. The numerals in the circles are the shortage and excess number of bicycles. At the red port, there are three excess bicycles. Thus, the vehicle must load three bicycles. At the blue port, there is a shortage of three bicycles. Thus, the vehicle must supply three bicycles; however, only one bicycle is supplied in this example.

In Equation (18), α and β are the weight parameters of the penalty. If the parameters are set to a large value, a small constraint violation becomes a large penalty. Nonetheless, it is possible to search for a solution that sufficiently satisfies the mBSSRP constraints. In the actual relocation operation, it may not be possible to obtain a solution that satisfies all of the constraints, i.e., we may not be able to find a feasible mBSSRP solution. In such a case, adjusting the values of α and β , we can decide on a priority order for the constraints.

3. Heuristic Methods

An optimal solution can be obtained by using an exact algorithm using the mBSSRP formulation and a general-purpose MIP solver. However, for an instance with a large number of ports, it is almost impossible to obtain an optimal solution in a reasonable time frame using the exact algorithm. Therefore, we used an approximation algorithm, a construction method, local search methods and the tabu search as a meta-heuristics method. The construction method is used to construct an initial solution. The local search methods ensure decent downhill dynamics. The tabu search is used to escape from local minima.

The proposed method can find a solution to mBSSRP or mBSSRP-S in three steps. First, an initial tour is constructed by the construction method. Second, the initial solution is improved by the local search methods, consisting of the inserting method and the swapping method. Then, to find a good solution for mBSSRP, the execution of the CROSS-exchange and the Or-opt are controlled by the tabu search. Figure 2 is a flowchart of the proposed method. In the following subsections, we explain the construction methods, the local search methods and the tabu search in more detail.

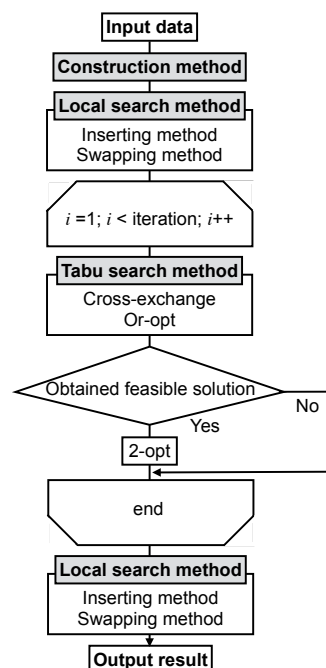


Figure 2. Flowchart of the proposed method. We construct an initial tour using the construction method. Then, we improve the initial tour using the inserting method and the swapping method. Next, the CROSS-exchange and the Or-opt are controlled by the tabu search and aim to transition to a feasible solution of mBSSRP. After feasible solutions of mBSSRP are obtained in the tabu search process, the 2-opt is executed. If we cannot obtain a feasible solution, the 2-opt method is not executed. Finally, to obtain better solutions, we execute the inserting method and the swapping method again.

3.1. Construction Method

We introduce two construction methods. The first method constructs a feasible solution for the mBSSRP and the second constructs a feasible solution for the mBSSRP-S. The first construction method sequentially inserts a port into a current tour until all ports are visited by a vehicle. We refer to the first construction method as “the cheapest insertion method”. When a port is inserted into the current tour, the resulting new tour must satisfy the constraints of the mBSSRP. The algorithm of the first construction method is described as follows:

1. Port i is randomly selected. If the number of bicycles at port i is negative ($b_i < 0$), the vehicle departs from the depot after loading b_i bicycles, supplies b_i bicycles to port i and returns to the depot. However, if $b_i > 0$, the empty vehicle goes to port i to load b_i bicycles and returns to the depot. In Figure 3a, the red port is a randomly selected port, and the pink vehicle goes to the selected red port and returns to the depot.
2. An unvisited port k is inserted into the current tour. To insert the unvisited port into an edge (i, j) in the current tour, the cost $\Delta_{ikj} = t_{ik} + t_{kj} - t_{ij}$ is calculated for all unvisited ports k . If the sub-tour after inserting port k into the edge (i, j) cannot satisfy the constraints of the mBSSRP, this inserting operation is prohibited.
3. Port k , where the cost Δ_{ikj} is minimum, is inserted into edge (i, j) . In Figure 3b, the red port is inserted into the tour of the pink vehicle.
4. When no ports satisfy the constraints, another vehicle goes to the unvisited port nearest to the depot. Figure 3c shows such a case; the red port is inserted into the tour of the pink vehicle; however, the time limit constraint is not satisfied. Therefore, a new vehicle (yellow) goes to the unvisited port nearest to the depot and returns to the depot as shown in Figure 3d.

5. Steps 2 to 4 are repeated until all ports are visited once by one of the vehicles (Figure 3e).
6. If all vehicles are already used and there exist unvisited ports, the method cannot construct a feasible mBSSRP solution. In Figure 3f, the red port cannot be visited by any vehicle. This is an infeasible solution.

The second construction method is used for the construction of a feasible mBSSRP-S solution. We refer to this as “the farthest insertion method”. It is often used as one of the construction methods for solving the traveling salesman problem. The algorithm of the second construction method is described as follows:

1. We randomly select m ports, where m is the number of vehicles. In Figure 4, the number of vehicles is three. Each vehicle goes to one of the selected ports and returns to the depot. In Figure 4a, three red ports are randomly selected. In Figure 4b, the blue, yellow and pink vehicles go to one of the selected ports and return to the depot.
2. An unvisited port k , which is the farthest from the depot, is selected. In Figure 4c, the farthest port from the depot is shown in green.
3. Port k is inserted between port i and port j in the tour, where $\Delta_{ikj} = t_{ik} + t_{kj} - t_{ij}$ is minimized, which means that an increase in the tour length after the insertion of the farthest port is minimum. In Figure 4d, the farthest port (green) is inserted into the tour of the blue vehicle.
4. Steps 2 and 3 are repeated until all ports are visited once by one of the vehicles.

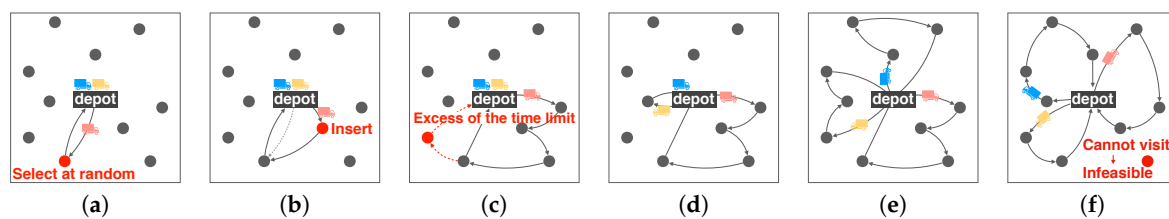


Figure 3. The cheapest insertion method. Black rectangles indicate depots and circles represent ports. (a) A red port is randomly selected and visited by the pink vehicle. (b) An unvisited port is inserted. (c) If the travel time of the pink vehicle exceeds the time limit after inserting the red port, (d) another vehicle (yellow) visits the nearest port from the depot. (e) An example of a feasible solution. (f) An example of an infeasible solution.

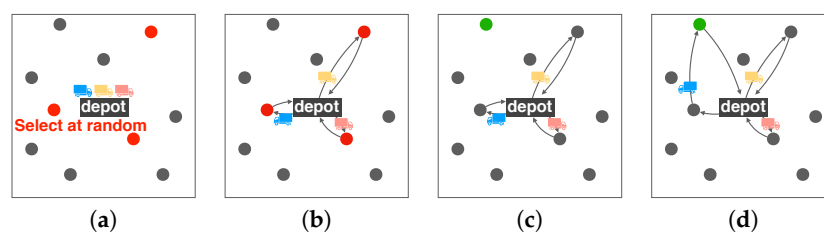


Figure 4. The farthest insertion method using three vehicles ($m = 3$). Black rectangles indicate depots and circles represent ports. (a) Three red ports are randomly selected. (b) The selected red ports are visited by the vehicles. (c) The farthest port (green) from the depot is selected. (d) The farthest port is inserted into the tour of the blue vehicle.

3.2. Local Search Methods

To improve the initial tour, the following five local search methods were used: the inserting method, the swapping method, the Or-opt [29], the CROSS-exchange [30] and the 2-opt method. While the inserting, the swapping and the 2-opt methods improved a single tour, the CROSS-exchange and the Or-opt improved the total travel time using two different tours.

In the inserting method, a partial tour whose length covers a maximum of three ports in a tour is inserted into an edge in the same tour. In Figure 5a, a partial tour $i' - k$ is

inserted into an edge (j, j') in the same tour. The swapping method swaps a partial tour for another partial tour in the same tour. In Figure 5b, a partial tour $i' - k$ is swapped for a partial tour $j' - l$. The Or-opt inserts a partial tour of a tour into an edge in another tour. In Figure 5c, a partial tour $i' - k$ in the orange tour is inserted into an edge (j, j') in the gray tour. In the Or-opt, the number of vehicles can be reduced, because of the insertion of ports. The CROSS-exchange replaces a partial tour in a tour with a partial tour in another tour. In Figure 5d, a partial tour $i' - k$ in the orange tour is exchanged with a partial tour $j' - l$ in the gray tour. The neighborhood solutions of the CROSS-exchange include that of the Or-opt. The 2-opt method deletes two edges in a tour and adds two new edges in the tour. In Figure 5e, two edges $i - i'$ and $j - j'$ are deleted, and two new edges $i - j$ and $i' - j'$ are added. The 2-opt method is used to improve a current solution if the current solution is a feasible solution obtained during the searching process using the tabu search.

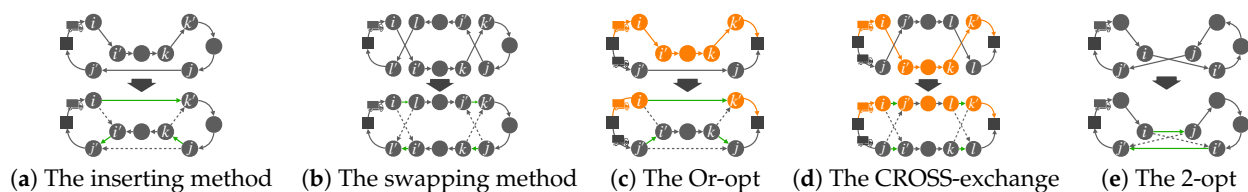


Figure 5. Five local search methods (a–e) used in this study. Black rectangles represent depots and gray and orange circles indicate ports. Letters in the circles indicate the port number. In these figures, dotted lines represent edges removed by the local search method, and green lines represent newly added edges.

3.3. Tabu Search Method

Most solutions obtained by the local search methods are locally optimal solutions but not the globally optimal solution. Hence, to find the globally optimal or near-optimal solutions, we used the tabu search [24–26]. The tabu search is one of the most powerful meta-heuristic strategies for solving combinatorial optimization problems. In the tabu search, to prevent a periodic search, previous solutions are stored in a tabu list for a certain amount of time. This duration is called a tabu tenure. During the tabu tenure, solutions are prohibited from moving to solutions in the tabu list.

In the proposed method, a current solution moves to the best neighborhood solution generated by the CROSS-exchange or the Or-opt. The combination of ports i' and j' (Figure 5c,d) is then stored in the tabu list. During the tabu tenure, the CROSS-exchange or the Or-opt cannot be performed on ports i' and j' because they are now in the tabu list. If a feasible mBSSRP solution is obtained using the tabu search method, the 2-opt algorithm is applied to the feasible solution to obtain a solution that is even better than the current one (Figure 5e). The tabu search explores the solution space of the mBSSRP through many iterations. Finally, the best solution obtained through the tabu search is further improved upon by using the inserting and the swapping methods (Figure 5a,b).

3.4. Dynamically Changing Weight of Penalties

When the penalty values in the mBSSRP-S objective function are zero, the solution is a feasible mBSSRP solution. In contrast, if one of the penalty values is larger than zero, the solution is an infeasible mBSSRP solution. To obtain feasible mBSSRP solutions from mBSSRP-S solutions, the parameters α and β in the mBSSRP-S objective function must be set to appropriate values. If the parameters are small, the penalty becomes weak even when the solution has several constraint violations. Then, the method tends to search the infeasible solution space of mBSSRP. Thus, it is difficult to obtain a feasible mBSSRP solution. If the parameters α and β are large, the current solution moves to a solution space that has small constraint violations, because these slight constraint violations result in a strong penalty. To perform an effective solution search for a good mBSSRP solution, the values of the parameters α and β must be adjusted in accordance with the solution states.

To adjust these values, we introduced a strategy based on a method for solving the vehicle routing problem with time window (VRPTW) [31]. The objective of the VRPTW is to find the shortest tour that serves all customers while satisfying the capacity, time limit and time window constraints associated with each customer. It is difficult to find a feasible solution for the VRPTW due to multiple constraints. To relax the constraints of the VRPTW, the vehicle routing problem with soft time windows (VRPSTW) was proposed. In the VRPSTW, the time windows can be violated if a penalty is paid. To find feasible VRPTW solutions, the weight penalty for the time windows is dynamically changed to obtain many feasible VRPTW solutions [31].

Thus, for the mBSSRP-S study, we extended this method [31] to dynamically adjust the weights of the penalties. In VRPSTW [31], there is a single weight parameter, while in mBSSRP-S, there are two weight parameters α and β . Thus, we had to consider how to change the values of two parameters. To adjust the weights of the penalties dynamically, the objective function of the mBSSRP-S was modified as follows:

$$z(t) = \sum_{i \in V} \sum_{j \in V} \sum_{k \in K} t_{ij} x_{ijk} + \alpha(t) p_T(t) + \beta(t) (p_{q+}(t) + p_{q-}(t)), \quad (19)$$

where $z(t)$ is the objective function of the mBSSRP-S at time t ; $\alpha(t)$ and $\beta(t)$ are the weights of the penalties for the time limit constraint and the loading and supplying constraints, respectively; $p_T(t)$ is the excess work time at time t , which extends beyond the time limit T ; $p_{q+}(t)$ refers to the loading violation of the bicycles at time t , where loading violation is defined as the total number of bicycles exceeding the loading capacity of the vehicle; $p_{q-}(t)$ refers to the supplying violation, representing the total number of bicycles that could not be supplied.

In this method, if a feasible solution is obtained at time t , the weight parameter is decreased, making it is easy to move to an infeasible solution at time $t + 1$. However, if an infeasible solution is obtained at time t , the weight parameter is increased, making it easy to move to the solution with small constraint violations at time $t + 1$. In this study, we propose two methods for adjusting the weights of the penalties.

The first method (Method 1) updates the weights through the following equations:

$$\alpha(t+1) = \begin{cases} \lambda \alpha(t), & \text{if } p_T(t) > 0, \\ \mu \alpha(t), & \text{if } p_T(t) = 0, \end{cases} \quad (20)$$

and

$$\beta(t+1) = \begin{cases} \lambda \beta(t), & \text{if } p_{q+}(t) + p_{q-}(t) > 0, \\ \mu \beta(t), & \text{if } p_{q+}(t) + p_{q-}(t) = 0, \end{cases} \quad (21)$$

where the parameter λ is an increasing parameter ($\lambda > 1$) and the μ is a decreasing parameter ($0 < \mu < 1$). If the penalty of a solution at time t is positive, the value of the weight corresponding to the penalty is increased. In contrast, if a penalty value is zero, the corresponding weight is decreased. After updating the weights, if the values of the weights are less than 1.0, the weights are set to unity ($\alpha(t+1) = 1$ or $\beta(t+1) = 1$).

If the solution violates both penalties, Method 1 increases the weights of both constraints to find a solution with a lower penalty at the time of the next iteration. As the weight increases, the searching strategy becomes almost identical to the search used for the feasible mBSSRP solution space.

To search the infeasible mBSSRP solution space widely, we introduced a second method (Method 2). In Method 2, when the solution violates both constraints, first, the values of penalty for the time limit and the loading and supplying constraint are compared. If the penalty of the time limit constraint is larger than that of the loading and supplying constraint, only the weight of the time limit penalty $\alpha(t)$ is increased. Although the solution violates the loading and supplying constraint, $\beta(t)$ is decreased. Meanwhile, if the penalty of the loading and supplying constraint is larger, $\beta(t)$ is increased and $\alpha(t)$ is decreased. In a combinatorial

optimization problem, good solutions have similar structures. Hence, there may be other feasible shorter mBSSRP tours around the feasible mBSSRP solution. In Method 2, if $p_T(t) = 0$ or $p_{b+}(t) + p_{b-}(t) = 0$, the corresponding $\alpha(t)$ or $\beta(t)$ is not updated.

Method 2 updates the weights as follows:

$$\alpha(t+1) = \begin{cases} \lambda\alpha(t) & \text{if } \alpha(t)p_T(t) > \beta(t)(p_{q+}(t) + p_{q-}(t)), \text{ and } p_T(t) \neq 0, \\ \mu\alpha(t) & \text{if } \alpha(t)p_T(t) < \beta(t)(p_{q+}(t) + p_{q-}(t)), \text{ and } p_T(t) \neq 0, \\ \alpha(t) & \text{if } \alpha(t)p_T(t) = \beta(t)(p_{q+}(t) + p_{q-}(t)), \text{ and } p_T(t) \neq 0, \\ \alpha(t) & \text{if } p_T(t) = 0, \end{cases} \quad (22)$$

and

$$\beta(t+1) = \begin{cases} \lambda\beta(t) & \text{if } \alpha(t)p_T(t) < \beta(t)(p_{q+}(t) + p_{q-}(t)), \text{ and } p_{q+}(t) + p_{q-}(t) \neq 0, \\ \mu\beta(t) & \text{if } \alpha(t)p_T(t) > \beta(t)(p_{q+}(t) + p_{q-}(t)), \text{ and } p_{q+}(t) + p_{q-}(t) \neq 0, \\ \beta(t) & \text{if } \alpha(t)p_T(t) = \beta(t)(p_{q+}(t) + p_{q-}(t)), \text{ and } p_{q+}(t) + p_{q-}(t) \neq 0, \\ \beta(t) & \text{if } p_{q+}(t) + p_{q-}(t) = 0. \end{cases} \quad (23)$$

Thus, if both the time limit and the loading and supplying constraints are violated, in Method 1, both parameters $\alpha(t)$ and $\beta(t)$ are increased. In Method 2, the parameters $\alpha(t)$ and $\beta(t)$ are adjusted after comparing the time limit penalty with the loading and supplying constraint penalty. If the penalties associated with the time limit and the loading and supplying constraints equal 0, both parameters $\alpha(t)$ and $\beta(t)$ are decreased in Method 1; however, the parameters $\alpha(t)$ and $\beta(t)$ are not updated in Method 2. After updating the weights, if the values of the weights are less than unity, then they are set to unity ($\alpha(t+1) = 1$ or $\beta(t+1) = 1$).

4. Numerical Experiments

To evaluate the performance of the proposed method, we built a benchmark problem for the mBSSRP. We distributed $n = 10, 30, 50$ ports uniformly in a 10 km^2 region. The number of bicycles at port i , b_i was set to a random number integer between -5 and $+5$ at intervals of 1. Note that $\sum_{i=1}^n b_i = 0$. The number of vehicles was set to a maximum of three. In applying the CROSS-exchange and the Or-opt, if the constraints are satisfied and the number of tours can be decreased, the number of vehicles is decreased such that the relocation of bicycles is performed by one or two vehicles. The capacity of the vehicle was $q = 5$. The moving speed of the vehicle was 30 [km/h] . The loading or unloading time of a bicycle was $\tau = 2 \text{ [min]}$. The time limit T was 120 [min] for $n = 10$ and 30 and 210 [min] for $n = 50$.

4.1. Results of the MIP Solver

First, we performed numerical experiments to find an optimal solution using the mBSSRP formulation and the MIP solver. For the simulation, we used the Gurobi optimizer 9.1.1 [17]. These numerical experiments were performed on an iMac with a 3.2-GHz 4-Core Intel Core i5 processor and 40 GB RAM. If an optimal solution was not obtained within 12 h, then the best solution obtained within that period was output.

Table 3 presents the results of the numerical experiments. The first column contains the instance numbers, the second column provides the values of the objective function, and the third column provides the calculation times. If the CPU time was less than $43,200 \text{ [s]}$ ($=12 \text{ [h]}$), then an optimal solution was obtained by the Gurobi optimizer. According to Table 3a, for small-sized instances, the optimal solution was obtained for all instances in a short time. However, when the number of ports was increased to 30 or 50, the calculation times became prohibitively long. For instances 3 and 6 of $n = 30$ (Table 3b), no feasible solutions were obtained. For instance 2 of $n = 30$ (Table 3b) and all instances of $n = 50$ (Table 3c), no optimal solutions were found within 12 h. In such cases, the tables display the best solution obtained within the 12 h period.

4.2. Results of the Proposed Method

To evaluate the performance of the proposed method, we generated 50 initial solutions using the cheapest insertion method for the mBSSRP and the farthest insertion method for the mBSSRP-S. The tabu tenure was set to 20, and the number of iterations was set to 1000. The initial weights were set to $\alpha(0) = 1$ and $\beta(0) = 1$. The increasing λ and decreasing parameters μ were set to 1.05 and 0.7, respectively. In evaluating the solutions generated by our method, we used the gap between our solution and the optimal or best solutions (Table 3b,c). The gap is defined by the following equation:

$$\text{Gap}[\%] = \frac{\text{Obtained best solution} - \text{Optimal or Best solution}}{\text{Optimal solution}} \times 100. \quad (24)$$

Thus, small gaps indicate good performance. Tables 4–8 present the results. The first column provides the instance numbers and the second to fourth columns present the average gaps obtained after 50 trials of the proposed method with the best and worst gaps as determined from the optimal or best solution. The gaps were calculated using Equation (24). The fifth column states the number of feasible solutions obtained during 50 trials.

As observed in Table 4, the method that only searches the feasible solution space does not yield a feasible mBSSRP solution for $n = 30$ and 50. In Table 4a, “-” indicates that the feasible solutions are not obtained. Then, for instances 3, 5, 7, 9 and 10 of $n = 50$ (Table 4b), the best gaps take negative values, which means that the method exploring the feasible solution space obtained better solutions than those obtained by the Gurobi optimizer 9.1.1 in 12 h. From Table 4, we cannot obtain feasible solutions for most of the instances. These results indicate that it is difficult to find feasible mBSSRP solutions when only the feasible solution space is explored.

Therefore, to find feasible mBSSRP solutions, we solved the mBSSRP-S with fixed values of the weight parameters. Tables 5 and 6 present the results. With the Gurobi optimizer, it takes about 12 h for 30 ports, and more than 12 h for 50 ports to obtain feasible solutions. Such long times are not realistic. Meanwhile, the average calculation times of the proposed method are 14.7 [s] ($n = 30$) and 56.5 [s] ($n = 50$). Therefore, the proposed method can obtain better results, in a time shorter than that required by the Gurobi optimizer.

As observed in Tables 4a and 5a, the method that explores both feasible and infeasible solution spaces of the mBSSRP obtains many feasible solutions compared to the method that searches only the feasible solution space. In addition, according to Table 5a,b, when the parameters α and β have large values, the number of feasible solutions increases, and the average gap indicates that the method performs well. Moreover, the method that explores both the feasible and infeasible solution spaces finds optimal solutions for multiple instances. The difference between the best and worst gaps is large for $n = 30$ (Table 3). Tables 4b and 6 indicate that for $n = 50$, we can obtain numerous feasible solutions when the parameters α and β have large values.

Table 3. Optimal or near-optimal solution obtained by the Gurobi optimizer. Symbol “-” means that no feasible solutions can be found by the Gurobi optimizer 9.1.1 within 12 h. Symbol “*” means that an optimal solution can be obtained using the Gurobi optimizer 9.1.1 within 12 h. (a) $n = 10$. (b) $n = 30$. (c) $n = 50$.

(a)		
No.	Objective Function	CPU-Time [s]
1	45,346 *	1.31
2	32,530 *	0.21
3	63,209 *	1.37
4	27,522 *	0.43
5	45,971 *	1.20
6	32,828 *	1.44
7	38,623 *	1.82
8	40,304 *	1.20
9	41,640 *	0.76
10	31,825 *	0.93

(b)		
No.	Objective Function	CPU-Time [s]
1	80,740 *	307.61
2	78,903	43,200.00
3	-	-
4	73,681 *	1048.03
5	72,912 *	21,800.49
6	-	-
7	74,625 *	3499.36
8	68,347 *	1068.09
9	73,328 *	1347.61
10	66,403 *	219.87

(c)		
No.	Objective Function	CPU-Time [s]
1	101,119	43,200.00
2	100,356	43,200.00
3	82,201	43,200.00
4	95,257	43,200.00
5	96,297	43,200.00
6	107,727	43,200.00
7	93,003	43,200.00
8	93,003	43,200.00
9	84,409	43,200.00
10	88,029	43,200.00

Tables 7 and 8 present the results obtained using the method of dynamically adjusted parameters. From Tables 7 and 8, the number of feasible solutions is 50 for almost all instances. The difference between the best gap and the worst gaps is smaller than that of the fixed case, as can be observed in Tables 5 and 6. The results indicate that the weight adjusting method can effectively control the search in the feasible and infeasible solution spaces. However, there is no significant difference between Method 1 and Method 2.

Table 4. Results of exploring feasible solution space for solving the mBSSRP. Ave., Best and Worst represent the average, best and worst gaps calculated using Equation (24). Symbol “-” means that no feasible solutions can be obtained. The feasible solutions of the instances 3 and 6 ($n = 30$) cannot be found using the latest version of the Gurobi optimizer 9.1.1. For $n = 50$, negative values of the best gaps mean that the method can find better solutions than that found by the Gurobi optimizer 9.1.1 within 12 h. Symbol “*” means that an optimal solution can be obtained using the Gurobi optimizer 9.1.1 within 12 h. (a) $n = 30$. (b) $n = 50$.

(a)				
No.	Ave.	Best	Worst	# of Feasible
1	-	-	-	0
2	-	-	-	0
4	-	-	-	0
5	-	-	-	0
7	-	-	-	0
8	1.90	0.00 *	15.95	32
9	-	-	-	0
10	-	-	-	0
(b)				
No.	Ave.	Best	Worst	# of Feasible
1	-	-	-	0
2	-	-	-	0
3	4.59	-1.76	10.01	35
4	2.96	1.35	3.76	3
6	3.94	1.88	5.99	2
5	0.16	-3.92	3.81	11
7	3.44	-0.62	7.13	15
8	-	-	-	0
9	3.23	-0.63	5.25	20
10	0.79	-3.14	5.87	34

The searching processes used in Method 1 and Method 2 when solving mBSSRP-S are shown in Figure 6. The horizontal axis shows the number of iterations and the vertical axis shows the objective function value (Equation (19)). In Figure 6, it is observed that feasible mBSSRP solutions are not obtained (black circle) with 200 iterations in Method 1 and with 400 iterations in Method 2. The parameters $\alpha(t)$ and $\beta(t)$ were adjusted using Equations (20) and (21) in Method 1, and Equations (22) and (23) in Method 2. After these phases, as observed in Figure 6a, Method 1 finds several feasible mBSSRP solutions with 1000 iterations. However, Method 2 finds more feasible solutions than Method 1 according to Figure 6b. When the penalty value is zero, Method 2 does not update the penalty weight because the current value is appropriate for conducting a search on feasible mBSSRP solutions. Once feasible mBSSRP solutions are obtained, Method 2 conducts repeated searches for more feasible solutions.

Table 5. Results of the method using fixed values of weight parameters for $n = 30$. Symbol “-” means that no feasible solutions can be obtained. Feasible solutions of instances 3 and 6 cannot be found by the latest version of the Gurobi optimizer 9.1.1 within 12 h. Symbol “*” means that an optimal solution can be obtained using the Gurobi optimizer 9.1.1 within 12 h. (a) $\alpha = 200, \beta = 2000$. (b) $\alpha = 1000, \beta = 10,000$.

(a)				
No.	Ave.	Best	Worst	# of Feasible
1	2.40	0.00 *	5.89	21
2	0.79	0.00	4.68	41
4	0.82	0.00 *	2.46	3
5	1.48	0.40	4.05	9
7	-	-	-	0
8	1.17	0.00 *	4.41	23
9	-	-	-	0
10	1.16	0.00 *	9.98	40

(b)				
No.	Ave.	Best	Worst	# of Feasible
1	2.75	0.00 *	9.77	45
2	0.85	0.17	12.86	50
4	0.28	0.00 *	4.63	19
5	1.01	0.40	4.02	6
7	4.52	0.40	7.10	32
8	0.85	0.00 *	6.12	50
9	0.32	0.00 *	1.51	50
10	0.80	0.00 *	10.83	50

Table 6. Results of the method using fixed values of weight parameters for $n = 50$. Symbol “-” means that no feasible solutions can be obtained. Negative values of average and best gaps mean that the method can find better solutions than that found by using Gurobi optimizer 9.1.1 within 12 h. (a) $\alpha = 200, \beta = 2000$. (b) $\alpha = 1000, \beta = 10,000$.

(a)				
No.	Ave.	Best	Worst	# of Feasible
1	2.41	2.41	2.41	1
2	2.51	-0.41	9.21	13
3	4.36	-0.69	10.71	7
4	5.53	1.60	9.92	9
5	-0.57	-1.68	0.66	3
6	-0.23	-0.23	-0.23	1
7	3.58	1.19	6.31	3
8	-	-	-	0
9	3.06	-0.63	5.26	17
10	0.50	-3.14	5.13	19

(b)				
No.	Ave.	Best	Worst	# of Feasible
1	1.27	-1.61	5.87	47
2	2.57	-0.50	11.92	50
3	3.01	-2.11	13.31	49
4	3.59	-0.33	11.13	48
5	0.83	-3.92	4.80	50
6	3.23	-0.23	8.62	50
7	1.81	-0.69	8.06	50
9	4.33	-0.64	11.24	50
10	1.08	-3.44	9.78	50

Table 7. Results of gaps in the method that dynamically adjusts weights for $n = 30$. Feasible solutions of instances 3 and 6 cannot be obtained by the latest version of the Gurobi optimizer 9.1.1 within 12 h. Symbol “*” means that an optimal solution can be obtained using the Gurobi optimizer 9.1.1 within 12 h. (a) Method 1 (Equations (20) and (21)). (b) Method 2 (Equations (22) and (23)).

(a)				
No.	Ave.	Best	Worst	# of Feasible
1	2.03	0.00 *	5.74	48
2	1.08	0.00	4.13	48
4	0.43	0.00 *	3.21	50
5	1.75	0.00 *	6.18	35
7	5.19	0.40	10.18	41
8	0.38	0.00 *	3.51	50
9	1.22	0.00 *	5.33	50
10	3.44	0.00 *	12.36	50

(b)				
No.	Ave.	Best	Worst	# of Feasible
1	0.83	0.00 *	3.56	50
2	0.56	0.00	3.53	49
4	0.20	0.00 *	5.07	50
5	1.64	0.00 *	4.47	48
7	3.09	0.00 *	6.68	50
8	0.84	0.00 *	5.95	48
9	0.22	0.00 *	0.67	48
10	1.03	0.00 *	12.33	46

Table 8. Results of gaps in the method that adjust weight dynamically for $n = 50$. Negative values of average and best gaps mean that the methods can find better solutions than that found using the Gurobi optimizer 9.1.1 within 12 h. (a) Method 1 (Equations (20) and (21)). (b) Method 2 (Equations (22) and (23)).

(a)				
No.	Ave.	Best	Worst	# of feasible
1	0.26	−1.60	2.51	50
2	0.57	−0.41	3.15	50
3	1.55	−2.11	8.49	50
4	0.89	−0.33	6.49	50
5	−0.09	−3.30	3.43	50
6	1.73	−0.31	5.94	50
7	0.90	−0.69	6.56	50
9	2.02	−0.10	4.87	50
10	−1.32	−3.40	2.19	50

(b)				
No.	Ave.	Best	Worst	# of feasible
1	1.47	−1.66	5.47	50
2	2.24	−0.50	8.51	49
3	2.99	−2.11	11.48	49
4	2.20	−0.33	22.49	50
5	0.80	−3.61	7.60	50
6	3.60	−0.69	9.28	44
7	1.54	−0.69	6.89	48
9	3.23	−0.15	11.40	50
10	0.59	−3.39	10.78	38

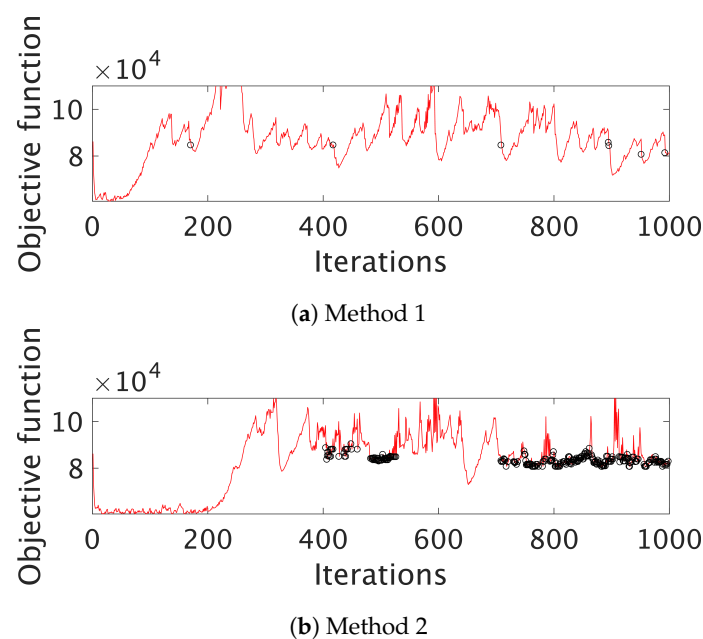


Figure 6. Temporal changes in the process for searching objective function values in (a) Method 1 and (b) Method 2 when solving the mBSSRP-S ($n = 30$). Black circles represent when the method finds feasible solutions of the mBSSRP. Results show that Method 2 finds more feasible solutions than Method 1 during 1000 iterations.

5. Conclusions

In this study, to adjust the number of bicycles at ports in BSS, we solved the mBSSRP. However, it is difficult to obtain feasible mBSSRP solutions because of strict constraints such as the time limit, the capacity and the loading and supplying constraints.

Thus, to find feasible solutions for problems with strict constraints, we developed a strategy of searching not only the feasible solution space but also the infeasible solution space. To explore both the feasible and infeasible mBSSRP solution spaces, we introduced the mBSSRP-S formulation whereby some constraints were removed and penalties were added to the objective function for constraint violation. In addition, we introduced two methods for dynamically adjusting the weights of the penalties, to enhance performance, by effectively searching the feasible and infeasible solution spaces.

The results of the numerical experiments demonstrated that the proposed method could find feasible solutions for almost all benchmark problems while identifying the optimal solutions as well. Thus, it is effective to search both the feasible and infeasible solution spaces. Moreover, we could enhance the performance of our process by introducing a method for dynamically adjusting the weights for solving the mBSSRP-S; namely, we were able to explore the infeasible solution space of the mBSSRP effectively. In this study, we proposed a strategy of searching the feasible and infeasible solutions and showed that the proposed strategy works well for instances of mBSSRP with 30 and 50 ports.

In the future, to obtain an optimal solution for larger instances using the MIP solver, we will propose a more effective formulation with a smaller number of variables and constraints. Although we used flow formulation (FF) to eliminate sub-tours in our study, we also examined Miler, Tucker and Zemlin (MTZ) [32] formulation and conducted numerical experiments. With FF, an optimal solution was obtained in a shorter time, possibly due to the automatic cut generation function of the Gurobi optimizer. Although an important issue, this was not investigated any further as it was not the focus of the current study.

In the numerical experiments, we used original benchmark instances because there are no suitable research examples on BSS restoration. However, generating and sharing benchmark instances in this field as well as comparing the performance of the proposed

methods with existing ones are important issues to be addressed in the future. In addition, to find good near-optimal solutions for large-scale instances, we intend to implement algorithms using a meta-strategy, such as simulated annealing, genetic algorithm and ant colony algorithm, and compare the performances. With the current relocation operation, it may not be possible to obtain a solution that satisfies all conditions; namely, we may not be able to find a feasible mBSSRP solution. In such a case, we must prioritize the constraints.

In a real BSS, the number of bicycles and empty docks at each port will change during the relocation operation. Therefore, it is impossible to perfectly restore the BSS to its initial state. An operational goal of the BSS is to always satisfy the user demand: users can rent bicycles at any port and return bicycles to any port, any time during the day. To achieve this goal, we need to predict the travel demands of the users in order to efficiently relocate the bicycles by using the predicted data. To resolve this issue, it will be necessary to analyze the occupancy level [33] and to come up with an efficient prediction model [34], based on actual travel history data that are available for New York [35], Washington D.C. [36] and Boston [37].

In this study, we used scenarios that randomly placed ports and compared the performance of the proposed method, which explores both the feasible and infeasible solution spaces, with the one that explores only the feasible solution space. To apply the proposed strategy to real-world problems, different scenarios have to be entertained. One possible strategy is to use real-life information from the rented and returned bicycle data of actual travel history data [35–37]. This information would include the distribution of bicycles at each port as well as the use frequency of the ports. Using this information, more effective strategies can be designed to solve real-world problems. Introducing additional soft constraints could also be beneficial in improving the performance of real-world BSS.

In this study, to adjust and control the parameters α and β dynamically, we searched all neighborhood solutions of the CROSS-exchange and the Or-opt. However, a long time is needed to search for all neighborhood solutions of the CROSS-exchange and the Or-opt. When we deal with a larger number of ports or more complex problems with soft constraints, the calculation time further increases. Thus, as a future step, to reduce the calculation time, one of the possible directions is to reduce the number of neighborhood solutions by not searching all neighborhood solutions in the CROSS-exchange and the Or-opt.

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References

1. Meddin, R.D.P. The Bike-Sharing World Map. Available online: <https://bikesharingworldmap.com> (accessed on 18 August 2021).
2. Chemla, D.; Meunier, F.; Calvo, R.W. Bike sharing systems: Solving the static rebalancing problem. *Discret. Optim.* **2013**, *10*, 120–146. [\[CrossRef\]](#)
3. Wada, S.; Matsuura, T.; Numata, K. Heuristic Methods for the Bike-Sharing System Routing Problem. *J. Signal Process.* **2013**, *17*, 115–118. [\[CrossRef\]](#)
4. Lin, J.H.; Chou, T.C. A geo-aware and VRP-based public bicycle redistribution system. *Int. J. Veh. Technol.* **2012**, *2012*, 963427. [\[CrossRef\]](#)

5. Raviv, T.; Tzur, M.; Forma, I.A. Static repositioning in a bike-sharing system: Models and solution approaches. *EURO J. Transp. Logist.* **2013**, *2*, 187–229. [\[CrossRef\]](#)
6. Ho, S.C.; Szeto, W. A hybrid large neighborhood search for the static multi-vehicle bike-repositioning problem. *Transp. Res. Part B Methodol.* **2017**, *95*, 340–363. [\[CrossRef\]](#)
7. Forma, I.A.; Raviv, T.; Tzur, M. A 3-step math heuristic for the static repositioning problem in bike-sharing systems. *Transp. Res. Part B Methodol.* **2015**, *71*, 230–247. [\[CrossRef\]](#)
8. Dell’Amico, M.; Hadjicostantinou, E.; Iori, M.; Novellani, S. The bike sharing rebalancing problem: Mathematical formulations and benchmark instances. *Omega* **2014**, *45*, 7–19. [\[CrossRef\]](#)
9. Benchimol, M.; Benchimol, P.; Chappert, B.; De La Taille, A.; Laroche, F.; Meunier, F.; Robinet, L. Balancing the stations of a self service “bike hire” system. *RAIRO-Oper. Res.* **2011**, *45*, 37–61. [\[CrossRef\]](#)
10. Schuijbroek, J.; Hampshire, R.C.; Van Hoes, W.J. Inventory rebalancing and vehicle routing in bike sharing systems. *Eur. J. Oper. Res.* **2017**, *257*, 992–1004. [\[CrossRef\]](#)
11. Kloimüller, C.; Papazek, P.; Hu, B.; Raidl, G.R. Balancing Bicycle Sharing Systems: An Approach for the Dynamic Case. In *Evolutionary Computation in Combinatorial Optimization—EvoCOP 2014*; Blum, C., Ochoa, G., Eds.; LNCS; Springer: Berlin/Heidelberg, Germany, 2014; Volume 8600, pp. 73–84.
12. Makarova, I.; Boyko, A.; Pashkevich, A.; Tsybunov, E. Solving the Last Mile Problem by Creating DSS to Manage Bike Sharing Infrastructure Development. In *International Conference on Reliability and Statistics in Transportation and Communication*; Springer: Cham, Switzerland, 2020; pp. 357–366.
13. Lyu, Y.; Cao, M.; Zhang, Y.; Yang, T.; Shi, C. Investigating users’ perspectives on the development of bike-sharing in Shanghai. *Res. Transp. Bus. Manag.* **2020**, 100543, [\[CrossRef\]](#)
14. Torrisi, V.; Ignaccolo, M.; Inturri, G.; Tesoriere, G.; Campisi, T. Exploring the factors affecting bike-sharing demand: Evidence from student perceptions, usage patterns and adoption barriers. *Transp. Res. Procedia* **2021**, *52*, 573–580. [\[CrossRef\]](#)
15. Cheng, L.; Mi, Z.; Coffman, D.; Meng, J.; Liu, D.; Chang, D. The Role of Bike Sharing in Promoting Transport Resilience. *Networks Spat. Econ.* **2021**, 1–19. [\[CrossRef\]](#)
16. Tsushima, H.; Matsuura, T. Optimum restoration of the bicycles by using multiple vehicle in bike sharing system. In *Proceedings of the IEICE NOLTA Society Conference 2017*, Aichi, Japan, 6 June 2017; NLS-16. (In Japanese)
17. Gurobi Optimizer. Available online: <http://www.gurobi.com> (accessed on 18 August 2021).
18. Tsushima, H.; Matsuura, T.; Jin’no, K. Local Search Method for Multiple-Vehicle Bike Sharing System Routing Problem. *J. Signal Process.* **2018**, *22*, 157–160. [\[CrossRef\]](#)
19. Holland, J. *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Application to Biology, Control and Artificial Intelligence*; University of Michigan Press : Ann Arbor, MI, USA, 1975.
20. Kirkpatrick, S.; Gelatt, C.D.; Vecchi, M.P. Optimization by simulated annealing. *Science* **1983**, *220*, 671–680. [\[CrossRef\]](#)
21. Matsuura, T.; Ikeguchi, T. Chaotic motif sampler: Detecting motifs from biological sequences by using chaotic neurodynamics. *Nonlinear Theory Its Appl. IEICE* **2010**, *1*, 207–220. [\[CrossRef\]](#)
22. Morita, Y.; Kimura, T. An improved routing algorithm using chaotic neurodynamics for packet routing problems. *Nonlinear Theory Its Appl. IEICE* **2018**, *9*, 95–106. [\[CrossRef\]](#)
23. Fujita, M.; Kimura, T.; Ikeguchi, T. Solving the Steiner tree problem in graphs by chaotic search. *Nonlinear Theory Its Appl. IEICE* **2020**, *11*, 90–108. [\[CrossRef\]](#)
24. Glover, F. Tabu search-part I. *Orsa J. Comput.* **1989**, *1*, 190–206. [\[CrossRef\]](#)
25. Glover, F. Tabu search-part II. *ORSA J. Comput.* **1990**, *2*, 4–32. [\[CrossRef\]](#)
26. Glover, F.; Taillard, E. A user’s guide to tabu search. *Ann. Oper. Res.* **1993**, *41*, 3–28. [\[CrossRef\]](#)
27. Skorin-Kapov, J. Tabu search applied to the quadratic assignment problem. *ORSA J. Comput.* **1990**, *2*, 33–45. [\[CrossRef\]](#)
28. Gendreau, M.; Hertz, A.; Laporte, G. A tabu search heuristic for the vehicle routing problem. *Manag. Sci.* **1994**, *40*, 1276–1290. [\[CrossRef\]](#)
29. Or, I. *Traveling Salesman-Type Combinatorial Problems and Their Relation to the Logistics of Blood Banking*. Ph.D. Thesis, Northwestern University, Evanston, IL, USA, 1976.
30. Taillard, É.; Badeau, P.; Gendreau, M.; Guertin, F.; Potvin, J.Y. A tabu search heuristic for the vehicle routing problem with soft time windows. *Transp. Sci.* **1997**, *31*, 170–186. [\[CrossRef\]](#)
31. Watanabe, D.; Kimura, T. A Solving Method using The Chaos Search for The Vehicle Routing Problems with Soft Time Window Constraints. *Tech. Rep. IEICE* **2019**, *118*, 51–56. (In Japanese)
32. Miller, C.E.; Tucker, A.W.; Zemlin, R.A. Integer programming formulation of traveling salesman problems. *J. ACM (JACM)* **1960**, *7*, 326–329. [\[CrossRef\]](#)
33. Cagliero, L.; Cerquitelli, T.; Chiusano, S.; Garza, P.; Ricupero, G.; Baralis, E. Characterizing situations of dock overload in bicycle sharing stations. *Appl. Sci.* **2018**, *8*, 2521. [\[CrossRef\]](#)
34. Kaltenbrunner, A.; Meza, R.; Grivolla, J.; Codina, J.; Banchs, R. Urban cycles and mobility patterns: Exploring and predicting trends in a bicycle-based public transport system. *Pervasive Mob. Comput.* **2010**, *6*, 455–466. [\[CrossRef\]](#)
35. Citi Bike System Data. Available online: <https://www.citibikenyc.com> (accessed on 18 August 2021).
36. Capital Bikeshare System Data. Available online: <https://www.capitalbikeshare.com> (accessed on 18 August 2021).
37. BLUE Bikes System Data. Available online: <https://www.bluebikes.com> (accessed on 18 August 2021).

SELECTED PAPER AT NCSP'21

Possibility of Reconstructing Nonlinear Dynamical System from Marked Point ProcessKazuya Sawada¹, Yutaka Shimada² and Tohru Ikeguchi¹

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Abstract

We can observe marked point processes in a wide variety of natural phenomena. Thus, it is important to establish theories and methods for analyzing such observed marked point processes. In a nonlinear time series analysis, the theories are the embedding theorems and the methods are the state space reconstruction from the observed time series. Although it has been revealed that we can reconstruct a state space from a point process without marked values, it has not been clarified yet whether we can reconstruct the state space from a marked point process. Therefore, in this study, we numerically investigated whether a state space could be reconstructed from a marked point process using a delayed coordinate system. To assess the issue, we evaluated the similarity between the interpoint distance distributions on an attractor of the original dynamical system that generated the marked point process and an attractor reconstructed from the marked point process. Results of numerical experiments show that the interpoint distance distributions in the original and reconstructed state spaces are similar, implying that it is possible to reconstruct nonlinear dynamical systems from the observed marked point processes.

1. Introduction

In recent years, it has become possible to observe various time series data with high precision because observational technologies have been much improved. Then, we can observe marked point processes that are observed at irregular time intervals with a marked value. Typical examples of marked point process data include spike trains derived from neural activities, occurrence timings of seismic activities, and temporal fluctuations of economic indices.

Identifying causal relations only from the observed data would be useful to understand various phenomena. For example, using a method for detecting causality, we can estimate the network structure only from a multi-dimensional observed time series [1]. Thus, various methods for estimating causality from the observed time series, such as the Granger

causality [2] and the transfer entropy [3], have been proposed. However, it has been pointed out that these methods cannot distinguish actual causality from spurious causality and that they require a large number of data points [4]. On the other hand, a method called convergent cross mapping [4], based on the nonlinear dynamical system theory, has been proposed to resolve these issues.

We have already proposed a causality detection method for point processes [5–7] by modifying the convergent cross mapping. The proposed method detects causality based on information in the reconstructed state space. Then, we need to reconstruct an attractor from the marked point process. Although it is already known that we can reconstruct the attractor from event intervals of the point process [8–10], it has not been clarified yet whether we can reconstruct the attractor from a marked point process.

Therefore, in this study, we investigate the possibility of reconstructing the attractor of a nonlinear dynamical system from a marked point process. Considering the marked point process as a two-dimensional time series of event intervals and marked values, we evaluate the validity of the method of reconstructing the attractor from this two-dimensional time series.

2. Method for Generating Marked Point Processes

In this section, we describe how to generate a marked point process. We generated a marked point process by extracting local maxima of a continuous time series (Fig. 1) [11]. In Fig. 1, the n th event timing $S(n)$ is defined as that when the continuous time series takes the n th local maximum and the marked value $M(n)$ is its state value. Then, we define the n th interevent interval (IEI) as $T(n) = S(n+1) - S(n)$. To generate the continuous time series and marked point processes, we use the Lorenz system [12] as shown in Eq. (1).

$$\begin{cases} \dot{x} = \sigma(-x + y) \\ \dot{y} = -xz + rx - y \\ \dot{z} = xy - bz \end{cases} \quad (1)$$

where we use the parameter values $r = 28$, $\sigma = 10$, and

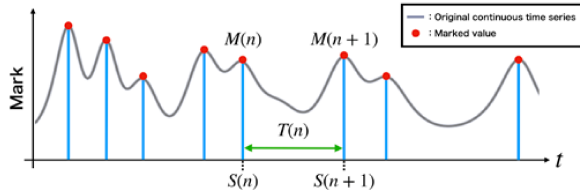


Figure 1: Schematic diagram of the method of generating a marked point process by extracting local maxima of an original continuous time series

$b = 8/3$ in this paper. These parameters are the most well-known parameters for generating a typical chaotic behavior, as first studied by Lorenz [12]. The reason why these parameters were used in Ref. [12] is that for $r > 24.74$, a chaotic response was obtained.

3. Evaluation of Reconstructed State Space from Marked Point Process

3.1 State space reconstruction from marked point process

We describe how to reconstruct a state space from the marked point process. First, we normalize the IEI time series $T(n)$ and marked value time series $M(n)$ to the range $[0, 1]$ by Eqs. (2) and (3).

$$\hat{T}(n) = \frac{T(n) - T_{\min}}{T_{\max} - T_{\min}} \quad (2)$$

$$\hat{M}(n) = \frac{M(n) - M_{\min}}{M_{\max} - M_{\min}} \quad (3)$$

where $T_{\max}$ and $T_{\min}$ are the maximum and minimum values of $T(n)$, and $M_{\max}$ and $M_{\min}$ are the maximum and minimum values of $M(n)$; $\hat{T}(n)$ and $\hat{M}(n)$ are the normalized IEIs and marked values. Then, the state space can be reconstructed using the delay coordinate system [13] as follows:

$$\mathbf{V}(n) = (\hat{M}(n), \hat{T}(n), \dots, \hat{M}(n + (m-1)\tau), \hat{T}(n + (m-1)\tau)) \quad (4)$$

where $2m$ is the reconstruction dimension and τ is the time delay. It seems reasonable to reconstruct the state space from the time series of IEIs and marked values because it has already been shown that the state space can be reconstructed from a multi-dimensional time series [14, 15].

If a nonlinear dynamical system can be reconstructed from the marked point process, several properties of the nonlinear dynamical system should be preserved in the reconstructed state space: the orbital instability characterized by the Lyapunov spectrum and the self-similarity of attractors characterized by the fractal dimension. If the topological characteristics of the dynamical system are preserved, the interpoint distance distributions of the original and reconstructed attractors will be similar. Therefore, to evaluate whether the origi-

nal dynamical system can be reconstructed, we calculate the Jensen–Shannon (JS) divergence [16] between the interpoint distance distributions in the original state space and the state space reconstructed from the marked point process obtained from the Lorenz system.

Then, we investigate whether the JS divergence between the interpoint distance distributions of the original state space and the state space reconstructed from the marked point process is sufficiently small. We also generate the random shuffle surrogate data (RSSD) of the marked point process and evaluate the JS divergence between the interpoint distance distributions of the original state space and the state space reconstructed from RSSD as a baseline in our analysis. We generate RSSD by randomly shuffling the temporal order of the normalized IEIs and marked values independently. We respectively define $T'(n)$ and $M'(n)$ as the randomly shuffled IEIs and marked values.

3.2 Jensen–Shannon (JS) divergence

The JS divergence [16] is defined as the sum of the Kullback–Leibler (KL) divergences. The KL divergence is a measure used to quantify the dissimilarity of two probability distributions. The KL divergence of a probability distribution P from a probability distribution Q is defined by

$$D_{KL}(P||Q) = \sum_{i=1}^N P(k_i) \log \left(\frac{P(k_i)}{Q(k_i)} \right) \quad (5)$$

where $P(k_i)$ and $Q(k_i)$ are the probabilities of the i th class of the probability distributions P and Q in ascending order and N is the total number of classes. In this study, we set $N = 20$ in all the numerical experiments. From Eq. (5), the KL divergence is an asymmetric measure, namely $D_{KL}(P||Q) \neq D_{KL}(Q||P)$ except in the case that $P(k_i) = Q(k_i)$ for all i .

The JS divergence for the probability distributions P and Q is defined by

$$D_{JS}(P, Q) = \frac{1}{2}(D_{KL}(P||R) + D_{KL}(Q||R)) \quad (6)$$

where the probability distribution R is the average of the probability distributions P and Q , and is defined by $R(k_i) = \frac{1}{2}(P(k_i) + Q(k_i))$.

3.3 Results

First, we numerically investigate whether we can evaluate the similarity between the interpoint distance distributions of the original attractor and an attractor reconstructed from the time series by calculating the JS divergence. Figure 2 shows the JS divergence between the interpoint distance distributions of the original Lorenz attractor and the attractors reconstructed from the time series of variables x , y , and z of the Lorenz system, where the reconstruction dimension varies in the range of $[2, 20]$ at intervals of 1. Here, we set the

time delay τ as four when we reconstruct the attractor. In Fig. 2, $D_{JS}(P_o, P_i)$ ($i \in \{x, y, z\}$) represents the JS divergence between the original state space of the Lorenz system and the state space reconstructed from the time series of the variable i ($i \in \{x, y, z\}$). In this study, we numerically solved the Lorenz equations using the fourth-order Runge–Kutta method with step size $h = 0.01$, where we excluded the first 100,000 data points as a transient state. Then, we used 10,000 data points to calculate the interpoint distance distribution. Namely, the number of interpoint distances is 49,995,000.

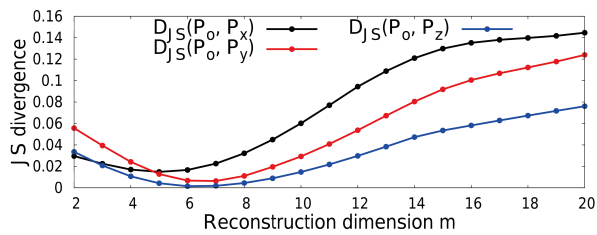


Figure 2: The JS divergence between the original Lorenz attractor and the attractors reconstructed from the time series of variables x , y , and z of the Lorenz system when m changes

From Fig. 2, we found that the JS divergence takes minimum values at the reconstruction dimensions of five for variable x and seven for variables y and z . The box-counting dimension of the Lorenz attractor is approximately 2.06 [17]; thus the reconstruction dimension that satisfies the condition for an embedding is five or more. Therefore, from Fig. 2, it is reasonable that the JS divergence is minimized at reconstruction dimensions of five for variable x and seven for variables y and z . These results suggest that the interpoint distance distributions of the original and reconstructed attractors are similar when the transformation by the delay coordinate can be an embedding as the reconstruction dimension is increased.

To discuss the reason why the JS divergence increases with the reconstruction dimension in Fig. 2, we show examples of the interpoint distance distributions of the original Lorenz attractor and the attractor reconstructed from the time series of variable z at reconstruction dimensions of 7 and 20 in Fig. 3. From Fig. 3, we found that the interpoint distance distributions of the original and reconstructed attractors are similar when the reconstruction dimension is seven. However, the peak of the frequency distribution of the interpoint distances of the reconstructed attractor (green) is larger when the reconstruction dimension is 20 (Fig. 3(b)). This is because the reconstructed state space becomes sparser as the dimension increases, and the interpoint distance becomes larger.

We next investigate whether the state space can be reconstructed from a marked point process by calculating the JS divergence of the interpoint distance distributions between the original and reconstructed attractors. First, we show the state spaces with and without trajectories reconstructed from

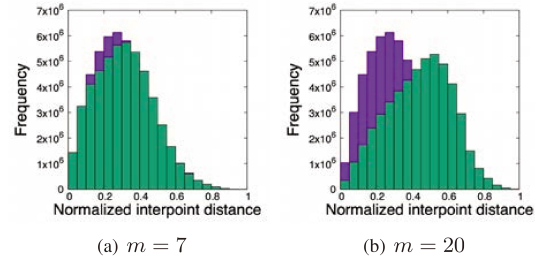


Figure 3: Frequency distributions of the interpoint distances of the original Lorenz attractor and the attractor reconstructed from the time series of variable z : The purple and green distributions are the interpoint distance distributions of the original and reconstructed state spaces, respectively.

the pair $(\hat{T}_x(n), \hat{M}_x(n))$ and the pair $(T'_x(n), M'_x(n))$ in Fig. 4. Here, we defined the normalized marked point process obtained by variable x of the Lorenz system as $\mathcal{M}_x$, and the normalized IEIs and marked values of $\mathcal{M}_x$ as $\hat{T}_x(n)$ and $\hat{M}_x(n)$, respectively. In addition, we defined the randomly shuffled normalized IEIs and marked values of $\mathcal{M}_x$ as $T'_x(n)$ and $M'_x(n)$, respectively. From Figs. 4(a) and (b), we found

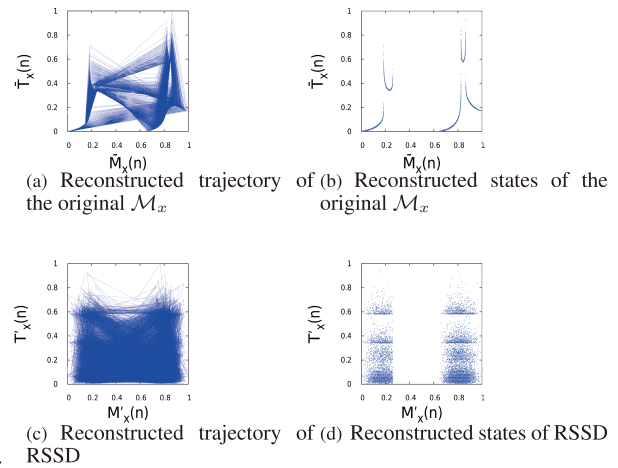


Figure 4: Reconstructed trajectories of the original $\mathcal{M}_x$ and RSSD

that the trajectory of $\mathcal{M}_x$ has a recurrence structure and that the points on the reconstructed state space follow deterministic dynamics. In contrast, from Figs. 4(c) and (d), the trajectory of RSSD has no structure and the points on the reconstructed state space do not follow any deterministic dynamics.

Then, we investigated the relationship between the JS divergence and the reconstruction dimension. Figure 5 shows the results of the JS divergence between the interpoint distance distribution of the original dynamical system and the interpoint distance distribution reconstructed from the marked point process in the case of changing the reconstruction dimension. In Fig. 5, we also show the range between the minimum and maximum values of the JS divergence of RSSD.

We generated ten RSSD for each value of m . We varied the reconstruction dimension in the range of $[2, 20]$ at intervals of 2. We set the time delay τ to unity.

In Fig. 5, the horizontal and vertical axes represent the reconstruction dimension and the JS divergence, respectively. In Fig. 5, $D_{JS}(P_o, P_{\mathcal{M}_i})$ represents the JS divergence between the original state space of the Lorenz system and the state space reconstructed from the marked point process of variable i ($i \in \{x, y, z\}$) and $D_{JS}(P_o, P'_{\mathcal{M}_i})$ ($i \in \{x, y, z\}$) represents the JS divergence between the original state space of the Lorenz system and the state space reconstructed from RSSD for each variable.

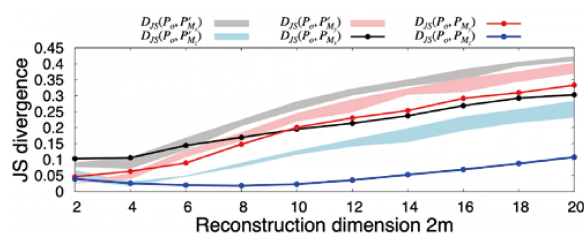


Figure 5: The JS divergence between the original Lorenz system and the system reconstructed from the marked point process $\mathcal{M}_i$ ($i \in \{x, y, z\}$) when m changes: The grey, red, and blue areas show the range from the minimum to maximum values when calculating the JS divergence of RSSD

From Fig. 5, we found that $D_{JS}(P_o, P_{\mathcal{M}_z})$ has a small value of less than 0.02 when $2m = 8$. Moreover, the values of $D_{JS}(P_o, P_{\mathcal{M}_z})$ are smaller than that of $D_{JS}(P_o, P'_{\mathcal{M}_z})$. In other words, the interpoint distance distribution reconstructed from the marked point process is similar to the interpoint distance distribution of the original state space. In addition, although $D_{JS}(P_o, P_{\mathcal{M}_x})$ and $D_{JS}(P_o, P_{\mathcal{M}_y})$ are larger than $D_{JS}(P_o, P_{\mathcal{M}_z})$, they are smaller than the JS divergences of RSSD, namely $D_{JS}(P_o, P'_{\mathcal{M}_x})$ and $D_{JS}(P_o, P'_{\mathcal{M}_y})$, when $2m \geq 6$. This condition $2m > 6$ might be closely related to the theorem [14] that a reconstruction dimension $> 2D_0$ is sufficient, where D_0 is the box-counting dimension. Because the box-counting dimension of the Lorenz attractor is approximately 2.06 [17], the minimum value of $2m$ that satisfies $D_{JS}(P_o, P_{\mathcal{M}_i}) < D_{JS}(P_o, P'_{\mathcal{M}_i})$ ($i \in \{x, y, z\}$) seems to satisfy the condition that $2m > 2D_0 \approx 4.12$.

On the other hand, in the cases of $D_{JS}(P_o, P_{\mathcal{M}_x})$ and $D_{JS}(P_o, P_{\mathcal{M}_y})$, the values of the JS divergence calculated from the original $\mathcal{M}_x$ and $\mathcal{M}_y$ are not significantly smaller than that of RSSD when the reconstruction dimension is small. The reason for this is presumably that for lower dimensions, especially for $2m \leq 4$, a one-to-one correspondence between the points on the reconstructed state space and the points on $\mathcal{M}_i$ does not exist; as shown in Fig. 4 (b), several points are not unfolded at lower dimensions. These points lead to a higher frequency of small distances, allowing the

value of the JS divergence to be larger than that of RSSD, even though there are no folded points in the original Lorenz attractor. Different from Fig. 2, the values for which the JS divergence is minimized do not appear clearly for all variables in Fig. 5. However, even though the peak value of the JS divergence does not appear, using the JS divergence of RSSD as a baseline, we might be able to infer an appropriate reconstruction dimension for an embedding when we only obtain a finite number of points of marked point processes.

4. Conclusion

We investigated whether a nonlinear dynamical system can be reconstructed from an observed marked point process using a delay-coordinate system by calculating the JS divergence between the interpoint distance distributions in the original state space and in the state space reconstructed from a marked point process and its randomly shuffled marked point process. As a result, it is shown that the trajectories of the attractors reconstructed from the marked point process had a more recurrence structure than those of the attractors reconstructed from RSSD. It is also shown that the interpoint distance distribution in the state space reconstructed from the marked point process is similar to that in the state space of the original Lorenz system.

In this paper, we evaluated the similarity between the reconstructed and original attractors in terms of the similarity of the interpoint distance distribution. However, it should also be evaluated in terms of dynamics. To evaluate the possibility of reconstructing the state space from a marked point process in terms of dynamics, it is an important issue to investigate the reconstructed attractor by evaluating the prediction accuracy or estimating the Lyapunov exponents. In addition, we investigated the similarity between the original and reconstructed Lorenz attractors for the parameter values of $r = 28$, $\sigma = 10$, and $b = 8/3$; however, it is also important in the future to investigate the similarity when we change the parameter values.

In this study, we did not theoretically clarify whether an embedding was satisfied by observing the marked point process from nonlinear dynamical systems. Then, another important future issue is to prove that the delay coordinates by marked point processes observed from nonlinear dynamical systems can be an embedding.

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References

- [1] K. Sawada, Y. Shimada and T. Ikeguchi: Network structure detection using convergent cross mapping on multivariate time series, *NOLTA, IEICE*, Vol. 11, No. 4, pp. 422-432, 2020.
- [2] C. W. J. Granger: Investigating causal relations by econometric models and cross-spectral methods, *Econometrica*, Vol. 37, No. 3, pp. 424-438, 1969.
- [3] T. Schreiber: Measuring information transfer, *Phys. Rev. Lett.*, Vol. 85, No. 2, pp. 461-464, 2000.
- [4] G. Sugihara, R. May, H. Ye, C. Hsieh, E. R. Deyle, M. Fogarty and S. Munch: Detecting causality in complex ecosystems, *Science*, Vol. 338, No. 6106, pp. 496-500, 2012.
- [5] K. Sawada, Y. Shimada and T. Ikeguchi: Estimation of connections between neurons only from inter-spike-interval, *Proc. 5th Int. Conf. on Mathematical Neuro-Science*, p. 80, 2019.
- [6] K. Sawada, Y. Shimada and T. Ikeguchi: Estimation of neural network structure using inter-spike intervals, *Proc. 2019 Int. Symp. Nonlinear Theory and its Applications*, pp. 591-594, 2019.
- [7] K. Sawada, Y. Shimada and T. Ikeguchi: Reconstruction of dynamical system from marked point process and its application to causality detection, *Proc. RISP Int. Workshop Nonlinear Circuits, Communications and Signal Processing 2021*, No. 1AM1-1-4, pp. 13-16, 2021.
- [8] T. Sauer: Reconstruction of dynamical systems from interspike intervals, *Phys. Rev. Lett.*, Vol. 72, No. 24, pp. 3811-3814, 1994.
- [9] T. Sauer: Interspike interval embedding of chaotic signals, *Chaos*, Vol. 5, No. 1, pp. 127-132, 1995.
- [10] T. Sauer: Reconstruction of integrate-and-fire dynamics, *Nonlinear Dynamics and Time Series*, Vol. 11, pp. 63-74, 1997.
- [11] N. Yabuta and T. Ikeguchi: Prediction of high-dimensional multivariate information as an amplitude-event dynamical system, *Proc. 2007 Int. Symp. Nonlinear Theory and its Applications*, pp. 16-19, 2007.
- [12] E. N. Lorenz: Deterministic nonperiodic flow, *J. Atmos. Sci.*, Vol. 20, No. 2, pp. 130-141, 1963.
- [13] F. Takens: Detecting strange attractors in turbulence, D. Rand, L.-S. Young (Eds.), *Dynamical Systems and Turbulence, Lecture Notes in Mathematics*, Vol. 898, Springer, Berlin, pp. 366-381, 1981.
- [14] T. Sauer, J. A. Yorke and M. Casdagli: Embedology, *J. Stat. Phys.*, Vol. 65, No. 3, pp. 579-616, 1991.
- [15] E. R. Deyle and G. Sugihara: Generalized theorems for nonlinear state space reconstruction, *PLOS ONE*, Vol. 6, No. 3, p. e18295, 2011.
- [16] J. Lin: Divergence measures based on the Shannon entropy, *IEEE Trans. Inf. Theory*, Vol. 37, No. 1, pp. 145-151, 1991.
- [17] P. Grassberger and I. Procaccia: Characterization of strange attractors, *Phys. Rev. Lett.*, Vol. 50, No. 5, pp. 346-349, 1983.

Paper

Performance evaluation of chaotic random numbers generated from responses of integer logistic maps

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Abstract: One of the engineering applications of chaotic nonlinear dynamical systems is a pseudorandom number generator. Pseudorandom numbers generated from chaotic dynamical systems are called chaotic random numbers. A logistic map which exhibits a chaotic response can be used as such a chaotic random number. However, an important issue exists when we use such dynamical systems as a pseudorandom number generator by a digital computer: when the chaotic response of a logistic map is reproduced numerically, the number of iterations that the chaotic response is sustained depends on the precision of the numerical calculation, because the precision of the numerical calculation affects the size of the numerical error. In this paper, we extended the logistic map to an integer logistic map to reduce such numerical errors. We investigated the performance of chaotic random numbers obtained from the integer logistic map with varying numerical precisions and transforming them into binary random numbers. We then used NIST SP 800-22 to evaluate the performance of the random numbers. The results show that a numerical precision of 20 orders of magnitude or more is desirable to the generation of a well-performing chaotic random numbers from the response of the integer logistic map.

Key Words: Chaotic random number, numerical calculation precision, and integer logistic map

1. Introduction

A random number sequence is an irregular and unpredictable sequence of numbers, each element of which is called a random number. One property expected of random numbers in any situation is unpredictability. Then, random numbers are employed in a wide range of applications, for example, setting initial values for cryptographic communications and numerical simulations.

On the other hand, chaos is a phenomenon that can be observed from deterministic nonlinear dynamical systems. One of the properties of deterministic chaos is sensitive dependence on initial conditions, wherein a small error in the initial conditions would expand over time. Then, it is difficult to predict responses produced from deterministic chaos in the long term due to such sensitive dependence on the initial conditions.

The long-term unpredictability of deterministic chaos is therefore potentially beneficial to the unpredictability required for random numbers, which has led to a number of research efforts on random number generation using deterministic chaos [1–12]. The random numbers generated using chaos, as in these references, are called chaotic random numbers. There are two main types of random number generation methods. One is physical random number generation, which is based on physical phenomena. For example, Uchida *et al.* proposed a high-speed physical random number generation method using laser chaos [13] that can greatly improve the random number generation speed, which is otherwise a drawback of physical random number generation methods. The other is pseudorandom number generation, which uses numerical calculations, such as the Mersenne Twister [14], which is a well-known pseudorandom number generation method.

In this paper, we discuss a chaotic random number generator that is classified as a pseudorandom number generator. The random numbers involved in this study are binary random numbers, i.e., 0 and 1. We focused on the generation of chaotic random numbers using a logistic map [15], which can be used to observe chaotic phenomena using a very simple mathematical formula. Although several studies [7, 16] have already been conducted on the generation of chaotic random numbers using the logistic map, they require post-processing methods, such as exclusive summation of multiple sequences, to improve the performance of the generated chaotic random numbers. One of the reasons why post-processing is necessary is that the numerical precision is insufficient for common double-precision floating-point operations. In a numerical simulation, it can be difficult to accurately reproduce the chaotic response due to the influence of numerical errors. In addition, the response converges to a periodic response or a fixed point because of the numerical calculation error. Therefore, we aim to reduce this error by increasing the precision of the numerical calculation. Namely, we generate chaotic random numbers based on the response of an integer logistic map [4, 17], which converts the decimal part to an integer part.

In [4], Ishida *et al.* evaluated the performance of chaotic random numbers generated from the responses of integer logistic maps from the viewpoint of the power spectrum [4]. However, this evaluation from the power spectrum perspective may not be sufficient from a statistical perspective. This is because the evaluation criterion is decided as follows: if the power spectrum of the generated chaotic random number is less than or equal to 0.6 for all the frequencies obtained, the number is considered as white noise and can be used as a pseudorandom number. In [6], Araki *et al.* proposed pseudorandom number generators using the logistic map and the integer logistic map with renewing the initial value. The renewal process of the initial value is introduced to avoid the convergence of the response to a periodic orbit caused by a finite numerical precision. In [11], Wang *et al.* evaluated the performance of a pseudorandom number generator that updates the bifurcation parameters of the logistic map. This process improved the confidentiality of the cipher by updating the bifurcation parameters.

In this study, we evaluated the performance of a pseudorandom number generator in a simple, natural and straightforward way: we only give an initial value and set numerical precision without any processing, such as the renewal of the initial condition or changing the bifurcation parameter. Then, we evaluated the performance of random numbers using the NIST [18] Special Publication 800-22 provided by the U.S. National Institute of Standards and Technology. The NIST test is an international standard statistical test method that is widely used and suitable for evaluating the

performance of fair random numbers.

In addition, we investigated the case that the bifurcation parameter a of the logistic map is negative, because it has already been shown that the chaotic response can be obtained even when the parameter a is negative [19]. Further, we investigated the performance of the pseudorandom number generator in relation to the values of the Lyapunov exponent by evaluating the number of passed NIST test items.

Therefore, this study has two objectives. The first is to investigate the performance of chaotic random numbers generated from an integer logistic map when the numerical calculation precision is changed. The second is to clarify which factors, other than numerical calculation precision, affect the random number performance.

2. Random number generators

The logistic map is a simple one-dimensional discrete time dynamical system [15]. The equation of the logistic map is described as:

$$x_{t+1} = f(x_t) = ax_t(1 - x_t), \quad (1)$$

where a is a bifurcation parameter and x_t is the state value at time t .

Figure 1 shows the bifurcation diagram of x_t when the value of a is changed in the range $-2.0 \leq a \leq 4.0$ [19]. The horizontal axis is for a , the left vertical axis is for the state value x_t (purple dots), and the right vertical axis is for the Lyapunov exponent λ (green crosses) which is defined to be

$$\lambda = \frac{1}{T} \sum_{t=1}^T |f'(x_t)|, \quad (2)$$

where T is the length of the time series. Figure 1 shows that λ can be greater than 0 regardless of the positive or negative value of a . The symmetric property in the Lyapunov exponent of the logistic map is discussed in [19], which showed that the Lyapunov exponents are symmetric about $a = 1.0$. Thus, λ for $a = 4.0$ and λ for $a = -2.0$ are equal and have the largest values ($\lambda = \ln 2$).

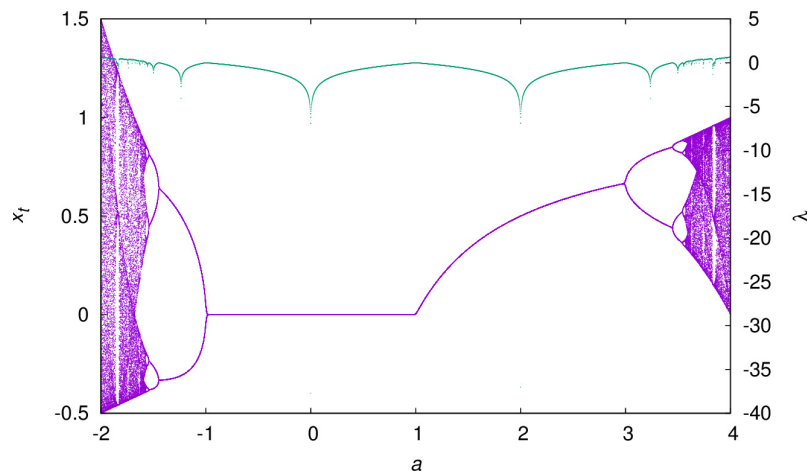


Fig. 1. Bifurcation diagram of x_t and the Lyapunov exponent λ of the logistic map.

Figure 2 shows the invariant measures when $a = 4.0$ and -2.0 . The horizontal axis represents the state value x_t , whereas the vertical axis represents the appearance probability $P(x_t)$. Figure 2 shows that $P(x_t)$ is symmetric about $x_t = 0.5$, whereas Fig. 3 shows the frequency proportion for $x_t < 0.5$ and $x_t > 0.5$, using the data from Fig. 2. In Fig. 3(a), the proportion of $x_t < 0.5$ is 0.499160, whereas the proportion of $x_t > 0.5$ is 0.500840. Meanwhile, in Fig. 3(b), the proportion of $x_t < 0.5$ is 0.499583, whereas the proportion of $x_t > 0.5$ is 0.500417. These values are expected to make the frequency distributions of 0 and 1 uniform when the random numbers are binarized.

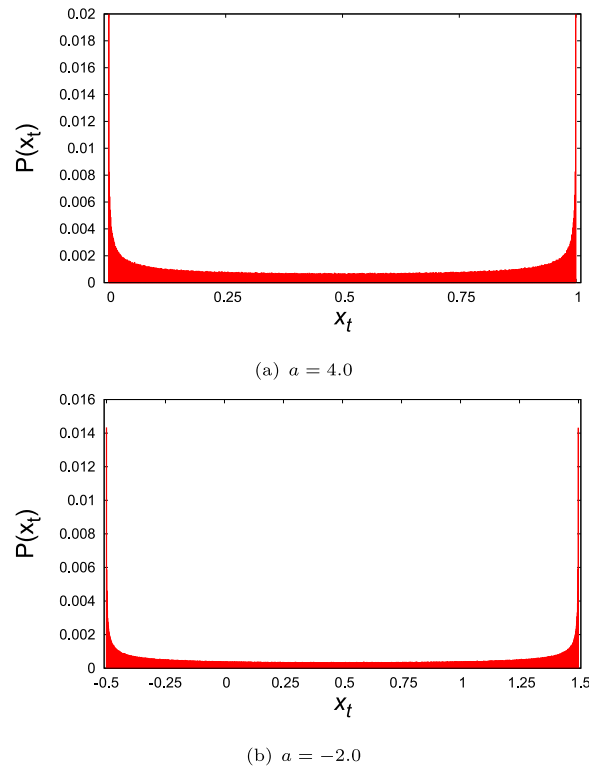


Fig. 2. Invariant measures of the logistic map for bifurcation parameters (a) $a = 4.0$ and (b) $a = -2.0$. In these cases, responses are chaotic, and the Lyapunov exponents are $\lambda = \ln 2$.

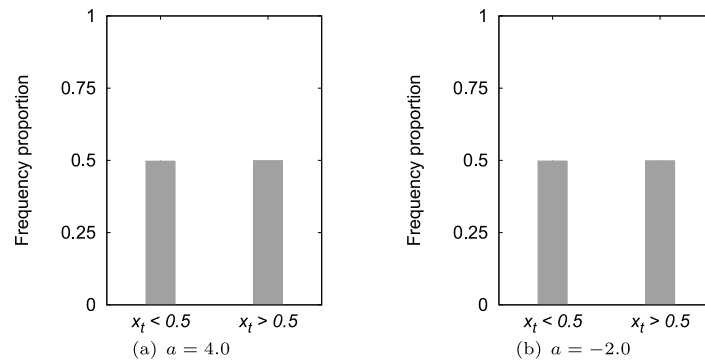


Fig. 3. Frequency proportion of binary values of the logistic map for (a) $a = 4.0$ and (b) $a = -2.0$.

In terms of the density function, we show that the frequencies of 0 and 1 are almost equal based on a binarization of the response of the logistic map. The invariant measure of the response for $a = 4.0$ in the logistic map is calculated using

$$P(x_t) = \frac{1}{\pi \sqrt{x_t(1-x_t)}}. \quad (3)$$

The product of x_t and $(1-x_t)$ appears in the square root of the denominator of Eq. (3), indicating that the probability density $P(x_t)$ of the logistic map, which is an interval dynamical system of $[0, 1]$, has symmetry with $x_t = 0.5$ as the center. Thus, if we binarize the response of the logistic map with $x_t = 0.5$ as the threshold, we can obtain a random number with an equal probability of occurrence.

On the other hand, because the numerical calculation precision is finite, the chaotic response of the

logistic map cannot be reproduced in the numerical simulation. Therefore, we extended the logistic map to an integer logistic map in decimal notation using [4]. The integer logistic map can be derived from Eq. (1). The procedure for extending the logistic map to the integer logistic map is as follows. First, multiplying the left term and the right term of Eq. (1) by 10^N , we obtain

$$10^N \times x_{t+1} = 10^N \times ax_t(1 - x_t). \quad (4)$$

With $X_t = 10^N \times x_t$, Eq. (4) is rewritten to

$$X_{t+1} = aX_t(10^N - X_t) \times 10^{-N}. \quad (5)$$

We use the floor function $\lfloor \cdot \rfloor$ to extract the integer part as follows:

$$X_{t+1} = \lfloor aX_t(10^N - X_t)10^{-N} \rfloor. \quad (6)$$

In Eq. (6), X_t is the state value of the integer logistic map at time t , and N represents the numerical precision.

We then explain how to make pseudorandom numbers from the integer logistic map. In this study, the parameter a is set to 4.0 and -2.0 , at which the Lyapunov exponent becomes $\ln 2$ and chaotic responses can be observed. We generate a time series from the integer logistic map (Eq. (6)) and convert it into binary random numbers using Eq. (7):

$$\tilde{X}_t = \begin{cases} 0 & (X_t \leq \theta), \\ 1 & (X_t > \theta), \end{cases} \quad (7)$$

where θ is a threshold. When $a = 4.0$, the range of the state values of the logistic map (Eq. (1)) is $0 \leq x_t \leq 1$. Thus, in the case of an integer logistic map (Eq. (6)), the range is $0 \leq X_t \leq 10^N$. If $a = -2.0$, the range of the integer logistic map is $-0.5 \times 10^N \leq X_t \leq 1.5 \times 10^N$. Thus, we set θ to 0.5×10^N , which is the median of the distributions of state values of the integer logistic maps in case that $a = 4$ or $a = -2$.

Figure 4 shows the results of generating chaotic random numbers from the response of the integer logistic map (Eq. (7)). In Fig. 4, the size of each image is $m \times m$ pixels, where $m = 800$. The (i, j) th pixel in Fig. 4(a)–(f) ($i, j = 0, 1, \dots, m - 1$) corresponds to X_{mi+j} , where the (i, j) th pixel is colored white if $X_{mi+j} \leq \theta$, and black otherwise. In Fig. 4, the upper row shows the generated random numbers when $a = 4.0$, and the lower row shows them when $a = -2.0$. The numerical calculation precision is set to $N = 7$, 15, and 20 from left to right.

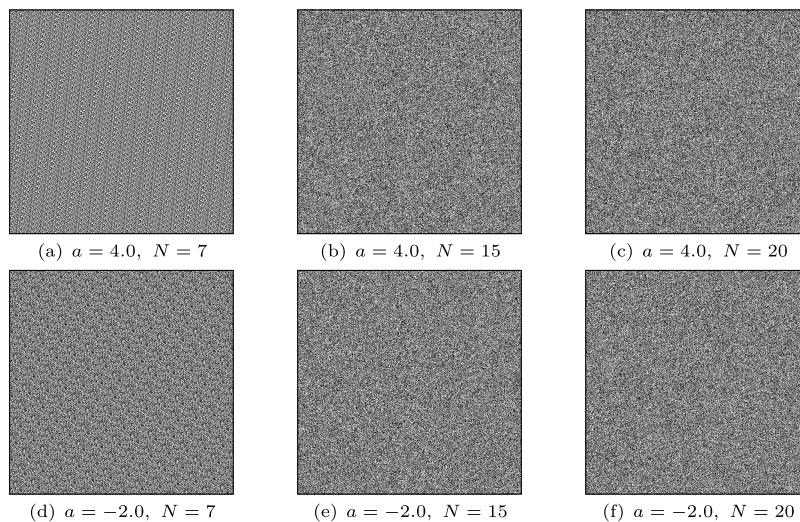


Fig. 4. Examples of binary random number sequences displayed on two-dimensional plane.

When $N = 7$, the generated random numbers exhibit a regular pattern, as shown in Fig. 4(a) and (d). On the other hand, when the precision of the numerical calculation is increased, the generated random numbers seem to be more random. However, to verify their randomness, the obtained random numbers have to be evaluated by a random number test method.

3. NIST SP 800-22

In this section, we describe the NIST test [18], which statistically evaluates whether a sequence of numbers is really random or not. The NIST test consists of 15 test items, which are listed with their respective test numbers, names, and descriptions in Table I. The NIST test in Table I is provided by the National Institute of Standards and Technology (NIST). Each test item in Table I tests properties required in random numbers.

Table I. Descriptions of 15 NIST test items [18].

No.	Items	Descriptions
1	Frequency Test	Test whether the occurrence probabilities of 0 and 1 are close to $\frac{1}{2}$.
2	Frequency Test within a Block	For a given block length, test whether the occurrence probabilities of 0 and 1 are close to $\frac{1}{2}$.
3	Cumulative Sums Test	Convert the binary random numbers to $(+1, -1)$ and test for the maximum deviation from 0 of the random walk defined by the cumulative sum.
4	Runs Test	Test for the number of consecutive 1s (runs).
5	Test for Longest Run of Ones in a Block	For a given block length, test for the longest runs.
6	Binary Matrix Rank Test	Test for the ranks of sparse matrices across several columns.
7	Discrete Fourier Transform Test	To investigate the periodicity, test for the height of the peak due to discrete Fourier transformation of the sequence.
8	Non-overlapping Template Matching Test	Test for the numbers of occurrences of bit string prepared in advance, without overlap.
9	Overlapping Template Matching Test	Test for the numbers of occurrences of bit string prepared in advance, with overlap.
10	Maurer's "Universal Statistical" Test	Detect and test matching patterns within a sequence, to see if they can be compressed.
11	Approximate Entropy Test	Test for the frequencies of occurrence of patterns of a given bit length.
12	Random Excursions Test	Test for the total number of times K is visited by cumulative sum random walks.
13	Random Excursions Variant Test	Test for the sum of the number of visits to a specific state with cumulative sum random walks.
14	Serial Test	Test for the occurrence frequencies of all overlapping bit patterns of a certain bit length.
15	Linear Complexity Test	Test for the length of the linear feedback register to generate a random number.

A random number sequence with a length of at least 1 Gbits is necessary to conduct the NIST test. If the random number sequence has a length of 1 Gbits, it is then divided into shorter segments with lengths of 1,000,000 (= 1 Mbits) each. Each of these 1,000 segments are then subjected to the 15 NIST test items. As a result, we obtain 1,000 p -values from each test.

The following two sub-tests are then conducted. In the first sub-test, the P -value, which indicates the uniformity of distribution of the 1,000 p -values, is obtained. Meanwhile, in the second sub-test, for each of the 1,000 p -values, we evaluate the probability that the p -value is greater than α ($= 0.01$), where the significance level α is the probability that the random number sequence is not random in the sense of each NIST item. A random number sequence is considered to have passed a certain test item if and only if it passes the first and second sub-tests for that item.

On the other hand, the parameter rules of the NIST test are important for obtaining an appropriate verification result according to the length of the random number sequence. Table II outlines the parameters used in this study. The values of the parameters in Table II were determined based on the method provided by NIST for setting the parameters [18].

Table II. Parameters used in NIST test [18].

Parameters	Values
Significance level α	0.01
Number of segments m	1,000
Frequency test within a block: Length of each block	16,384
Non-overlapping Template Matching Test: Length in bits of each template	9
Overlapping Template Matching Test: Length in bits of the template	9
Approximate Entropy Test: Length of each block	10
Serial Test: Length in bits of each block	16
Linear Complexity Test: Length in bits of a block	500

4. Experiments

In this study, we used the number of passed NIST test items, out of a total of 15 items, as an index of the performance evaluation of the generated random numbers. In addition, the binary random number sequences evaluated in this study were generated using 2^{30} ($= 1,073,741,824$) responses obtained from an integer logistic map after the first 100,000 responses were omitted as transient states.

Figure 5 shows the relationship between the number of passed NIST test items and the positive Lyapunov exponent λ of the logistic map. The horizontal axis is for the Lyapunov exponent λ , whereas the vertical axis represents the number of passed NIST test items. For the result shown, we had set the initial value $X_0 = 0.0002 \times 10^N$ and the numerical calculation precision $N = 20$. Then, we set the threshold θ to $\bar{x} \times 10^N$, where $\bar{x}$ is the average value calculated by

$$\bar{x} = \frac{1}{2^{30}} \sum_{t=1}^{2^{30}} x_t. \quad (8)$$

Figure 5 shows that the larger the value of λ , the larger the number of NIST test items that are passed, indicating that the orbital instability of the random number generator affects the performance of the generated random numbers. However, even when λ is positive, the number of passed NIST test items is particularly large when $a = 4.0$ and $a = -2.0$, at which λ is maximized ($\lambda = \ln 2$). From these results, the performance of chaotic random numbers generated from the integer logistic map is expected to improve only when a is 4.0 or -2.0 .

Meanwhile, Fig. 6 shows the results of examining whether the number of passed NIST test items changes between $a = 4.0$ and $a = -2.0$. The initial value was $X_0 = 0.0002 \times 10^N$, and the numerical

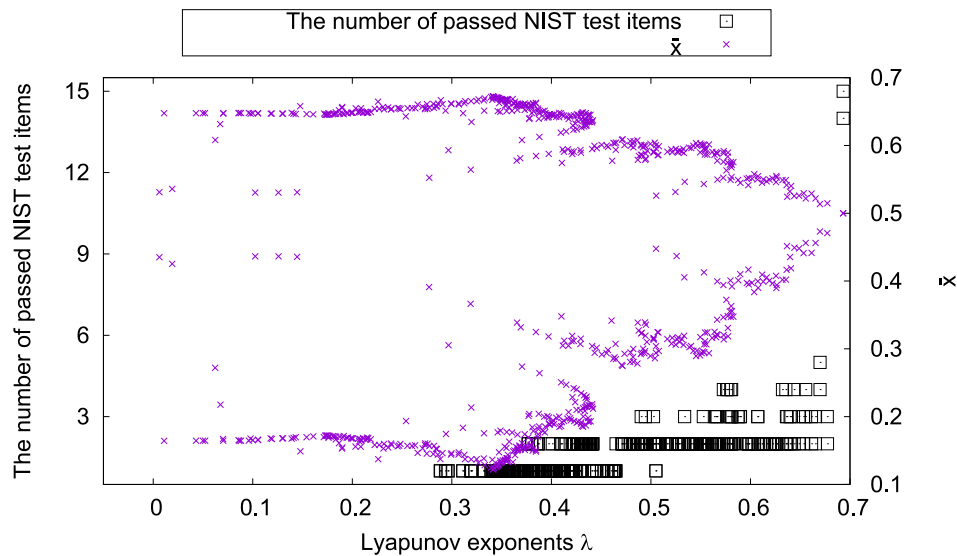


Fig. 5. Relationship between positive Lyapunov exponents λ and the number of passed NIST test items. The square marks denote the number of passed NIST test items, and the cross marks denote the average value $\bar{x}$.

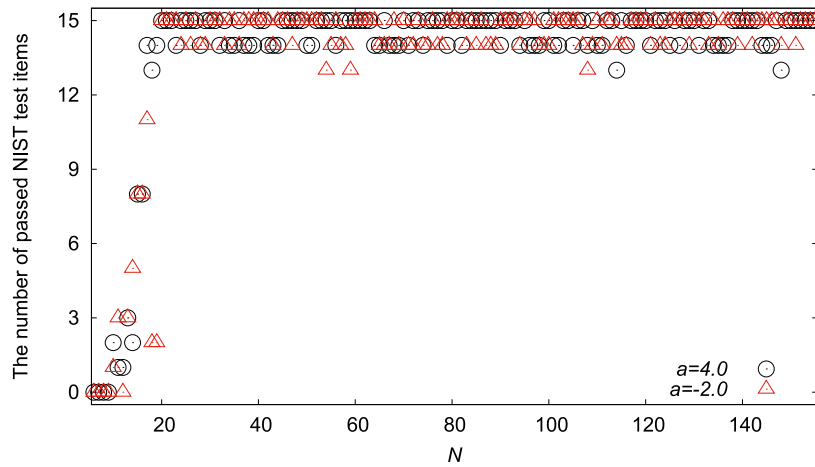


Fig. 6. The number of passed NIST test items for generated chaotic random numbers with respect to numerical calculation precision. Two bifurcation parameters were used: $a = 4.0$ (circles) and $a = -2.0$ (triangles).

calculation precision is in the range $6 \leq N \leq 155$. Then, we set θ as 0.5×10^N in the following analysis. The horizontal axis represents N , whereas the vertical axis represents the number of NIST test items that were passed. The results for $a = 4.0$ are shown as circles, whereas the results for $a = -2.0$ are shown as triangles. According to Fig. 6, the number of passed NIST test items is likely to be large when the numerical calculation precision is in the range $N \geq 20$ for both $a = 4.0$ and $a = -2.0$. To clarify the change in quality of generated random numbers with respect to the value of a , we further investigated the ratio of the number of passed NIST test items to the total number of items. The horizontal axis corresponds to the NIST test names listed in Table I, whereas the vertical axis represents the percentage of 150 random numbers with different N that passed these NIST test items. From Fig. 7, it can be seen that, for each test item, there is no difference in the distributions of the percentage due to the difference between $a = 4.0$ and $a = -2.0$. In addition, it is clear that both parameters occasionally fail in the Non-Overlapping Template Matching test, probably because of the nature of the logistic map used as the source of the random numbers.

On the other hand, Fig. 8 shows the results of generating chaotic random numbers as the precision of the numerical calculation is further increased. The horizontal axis represents the numerical calculation precision N , whereas the vertical axis represents the number of passed NIST test items. Because there was no difference in the performance of the random numbers generated when $a = 4.0$ and $a = -2.0$, we performed numerical experiments focusing on $a = 4.0$. Figure 8 shows that the higher the numerical precision N , the higher the performance of the generated chaotic random numbers.

However, when $N = 455$, the number of passed NIST test items dropped to 12. In addition, there are many cases wherein one item was rejected. These results imply that there are other factors than numerical calculation precision that may improve the number of passed NIST test items. If the performance of the chaotic random number is degraded even if the numerical precision is large, the initial value may be the cause.

Finally, we report the results of the investigation based on differences in the initial value X_0 . The numerical calculation precision N was investigated in the range $6 \leq N \leq 30$. We prepared 98 initial values (X_0) for each value of N , where we increased the value of X_0 in increments of 0.005 from 0.005×10^N to 0.495×10^N . Because the response of the integer logistic map converges to a fixed point when $X_0 = 0.25 \times 10^N$, we excluded $X_0 = 0.25 \times 10^N$ in this experiment. We investigated the performance of chaotic random numbers generated based on these values of N and X_0 . Figure 9 shows the results. The horizontal axis represents the numerical calculation precision N , whereas the vertical axis represents the average number of passed NIST test items based on the initial values for the 98 patterns. The error bars in Fig. 9 show the maximum and minimum numbers of NIST test items that were passed, whereas the histograms show the standard deviation.

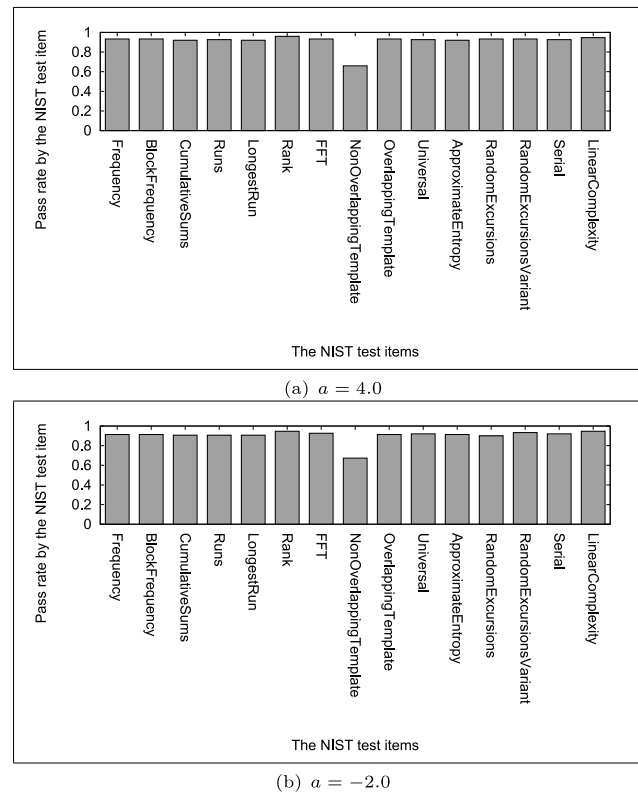


Fig. 7. Proportion of generated random numbers that passed each NIST test item for 150 values of N , with (a) $a = 4.0$ and (b) $a = -2.0$.

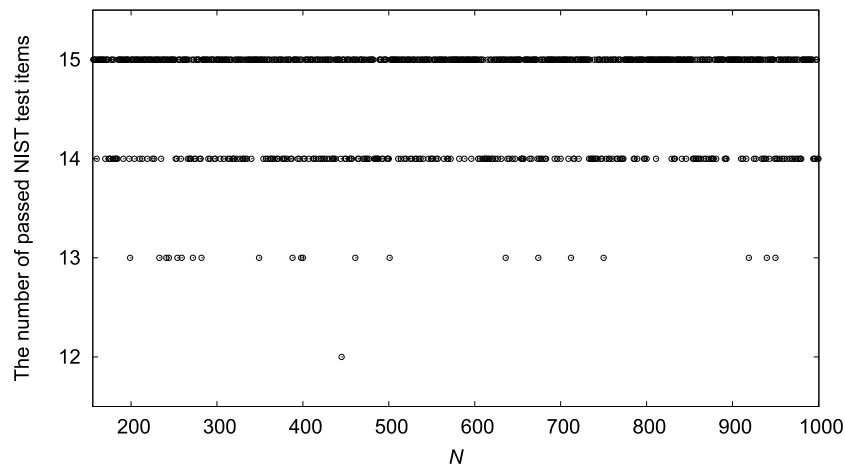


Fig. 8. The number of passed NIST test items when chaotic random numbers are generated as numerical calculation precision is varied from $155 < N \leq 1000$.

In the range $N \leq 9$, both the mean and standard deviation of the number of passed NIST test items were zero. Therefore, in this case, it is difficult to generate high-performance chaotic random numbers. On the other hand, when $N = 19$, the average number of passed NIST test items was high, but the minimum value was 6. Such performance differences depend on the initial value, suggesting that both the numerical calculation precision and the initial value are key factors that affect the performance of chaotic random numbers.

In the range $N \geq 20$, the average number of passed NIST test items was close to 15, and the standard deviation did not exceed unity, which means that if $N \geq 20$, the performance of pseudorandom

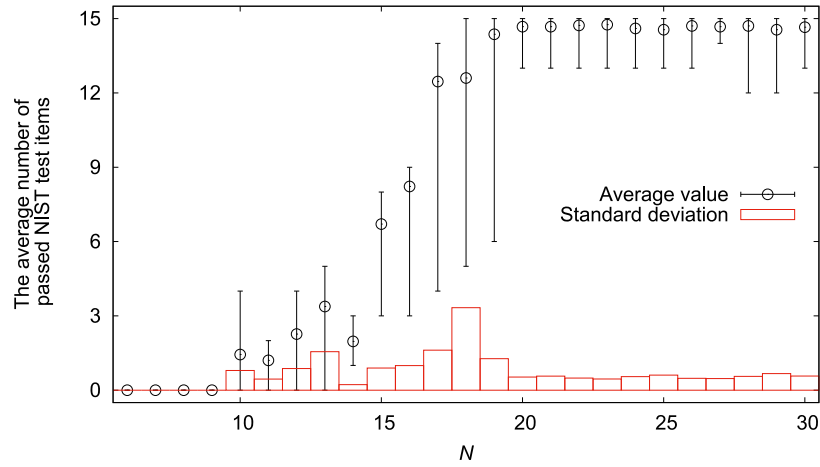


Fig. 9. Performance evaluation of generated chaotic random numbers with respect to numerical precision N and initial value X_0 .

numbers is high. Namely, to generate high-performance chaotic random numbers from the response of the integer logistic map, the precision of the numerical calculations must be at least 20.

5. Conclusion

In this study, we investigated the performance of chaotic random numbers and the factors that affect their performance improvement. To mitigate numerical calculation errors, we extended the logistic map to an integer logistic map and used it as a random number generation source. The integer logistic map allows calculations with arbitrary numerical precision, where the numerical precision is defined as the number of digits used in the numerical calculations of the state of the integer logistic map. To generate chaotic random numbers, we binarized the responses of the integer logistic map.

The performance of the generated chaotic random numbers was evaluated using NIST SP 800-22. The results of the numerical experiments indicate that the precision of the numerical calculation is a leading factor that affects the performance of the generated chaotic random numbers. In addition, both the numerical calculation precision and the initial value were inferred to affect the performance of the generated chaotic random numbers. In particular, it was suggested that the performance of the chaotic random numbers could be stabilized if the number of digits used for the numerical calculations was set to 20 or higher.

In this paper, we used the NIST test for evaluating the performance of pseudorandom numbers. However, it is also important to introduce other test suites, such as TestU01 [20]. Then, it is an important future work to verify the performance using these methods.

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References

- [1] S. Oishi and H. Inoue, “Pseudo-random number generators and chaos,” *Transactions of IEICE*, vol. E65, no. 9, pp. 534–541, 1982.
- [2] A. Arneodo and D. Sornette, “Monte Carlo random-walk experiments as a test of chaotic orbits of maps of the interval,” *Physical Review Letters*, vol. 52, no. 21, pp. 1857–1860, 1984.
- [3] S. C. Phatak and S. Suresh Rao, “Logistic map: A possible random-number generator,” *Physical Review E*, vol. 51, no. 4, pp. 3670–3678, 1995.
- [4] K. Ishida, A. Tsuneda, and T. Inoue, “Properties of chaotic sequences generated by finite-bit operations,” *Technical Report of IEICE*, vol. 98, no. 140, pp. 9–14, 1998, in Japanese.

- [5] G. Alvarez and S. Li, “Some basic cryptographic requirements for chaos-based cryptosystems,” *International Journal of Bifurcation and Chaos*, vol. 16, no. 8, pp. 2129–2151, 2006.
- [6] S. Araki, T. Miyazaki, S. Uehara, and K. Kakizaki, “A study on precision of pseudorandom number generators using the logistic map,” *2012 International Symposium on Information Theory and its Applications (ISITA)*, pp. 740–744, 2012.
- [7] M. François, T. Groses, D. Barchiesi, and R. Erra, “A new pseudo-random number generator based on two chaotic maps,” *Informatica*, vol. 24, no. 2, pp. 181–197, 2013.
- [8] A. Saito and A. Yamaguchi, “Pseudorandom number generation using chaotic true orbits of the Bernoulli map,” *Chaos: An Interdisciplinary Journal of Nonlinear Science*, vol. 26, no. 6, pp. 063122-1–063122-8, 2016.
- [9] K. Cho and T. Miyano, “Stream cipher using augmented Lorenz map and the evaluation of its performance,” *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, vol. J101, no. 8, pp. 210–218, 2018, in Japanese.
- [10] A. Tsuneda, “Orthogonal chaotic binary sequences based on Bernoulli map and Walsh functions,” *Entropy*, vol. 21, no. 10, pp. 930-1–930-9, 2019.
- [11] L. Wang and H. Cheng, “Pseudo-random number generator based on logistic chaotic system,” *Entropy*, vol. 21, no. 10, pp. 960-1–960-12, 2019.
- [12] S. Eguchi, T. Miyazaki, S. Araki, S. Uehara, and Y. Nogami, “A study on randomness of sequences obtained from piecewise logistic map over integers,” *2020 International Symposium on Information Theory and its Applications (ISITA)*, pp. 451–455, 2020.
- [13] A. Uchida, K. Amano, M. Inoue, K. Hirano, S. Naito, H. Someya, I. Oowada, T. Kurashige, M. Shiki, S. Yoshimori, K. Yoshimura, and P. Davis, “Fast physical random bit generation with chaotic semiconductor lasers,” *Nature Photonics*, vol. 2, no. 12, pp. 728–732, 2008.
- [14] M. Matsumoto and T. Nishimura, “Mersenne twister: a 623-dimensionally equidistributed uniform pseudorandom number generator,” *ACM Transactions on Modeling and Computer Simulations*, vol. 8, no. 1, pp. 3–30, 1998.
- [15] R. M. May, “Simple mathematical models with very complicated dynamics,” *Nature*, vol. 261, no. 5560, pp. 459–467, 1976.
- [16] V. Patidar, K. K. Sud, and N. K. Pareek, “A pseudo random bit generator based on chaotic logistic map and its statistical testing,” *Informatica*, vol. 33, no. 4, pp. 441–452, 2009.
- [17] J. Dong, “Random numbers generation method and the application by integer logistic map,” *Doctoral dissertation, The University of Electro-Communications*, 2012, in Japanese.
- [18] L. Bassham, A. Rukhin, J. Soto, J. Nechtratal, M. Smid, S. Leigh, M. Levenson, M. Vangel, N. Hecket, and D. Banks, “A statistical test Suite for random and pseudorandom number generators for cryptographic applications,” *National Institute of Standards and Technology, Special Publication 800–22*, 2010.
- [19] Y. Shimada, E. Takagi, and T. Ikeguchi, “Symmetry of Lyapunov exponents in bifurcation structures of one-dimensional maps,” *Chaos: An Interdisciplinary Journal of Nonlinear Science*, vol. 26, no. 12, pp. 123119-1–123119-2 2016.
- [20] P. L’Ecuyer and R. Simard, “TestU01: A C library for empirical testing of random number generators,” *ACM Transactions on Mathematical Software (TOMS)*, vol. 33, no. 4, pp. 1–40, 2007.

Paper

Analysis on the mechanism of enhancing insulin secretion by TRPM2 channel in a pancreatic β -cell

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Abstract: It has been reported that the activation of the Ca^{2+} -permeable transient receptor potential melastatin2 (TRPM2) channel enhances a pancreatic β -cell's insulin secretion. Further, it increases the resting potential, and prolongs the burst duration of the pancreatic β -cell. However, the mechanism by which the TRPM2 channel activation enhances insulin secretion is unknown. Therefore, in this paper, using a mathematical model that represents the dynamics of the membrane potential, we investigate the reproducibility of the results obtained from physiological experiments, and reveal the mechanism of enhancing insulin secretion. We demonstrate that the TRPM2 channel activation prolongs the burst duration when the TRPM2 reversal potential is close to the value observed in the physiological experiments. This could be a plausible theoretical explanation of the experimental value of the TRPM2 reversal potential. In addition, we reveal that the TRPM2 channel activates the voltage-dependent and Ca^{2+} -sensitive channels with large conductance, thereby inducing insulin secretion.

Key Words: pancreatic β -cell, TRPM2 channel, insulin secretion

1. Introduction

Insulin is secreted by the pancreatic β -cells in the islet of Langerhans. Insulin is a critical regulator of metabolism so that pancreatic β -cell dysfunction leads to both type 1 and type 2 diabetes. In type 1 diabetes condition, the body no longer produces insulin, and in type 2 diabetes condition, the produced insulin is not enough or does not work effectively. It is widely known that the membrane excitability of the pancreatic β -cell leads to the insulin secretion [1]. Therefore, it is important to preserve the membrane excitability of the pancreatic β -cell to prevent from insulin secretory dysfunction. However, the detailed mechanism of how pancreatic β -cell dysfunction leads to the insulin secretory dysfunction is still unknown [2, 3].

It is generally difficult to investigate the properties of ion channels in pancreatic β -cells. Then, several mathematical models have been proposed to clarify these properties. Chay and Keizer proposed a pioneering model of the pancreatic β -cells incorporating a Hodgkin-Huxley type gating mechanism for Ca^{2+} and K^+ channels [4]. Since then several models have been proposed including those of human β -cells [5]. Although these models are simple and are able to partly reproduce experimental results of the pancreatic β -cells, their ion channel constitutions are not sufficient. For example, the closure of the adenosine triphosphate (ATP)-sensitive K^+ (KATP) channels triggers the membrane depolarization of a pancreatic β -cell, and triggers insulin secretion. Riz et al. proposed a detail mathematical model of the pancreatic β -cells incorporating 12 types of ion channels including KATP channel [6]. This model describes a detailed ion channel mechanism of the pancreatic β -cells, which enables us to investigate the detailed membrane activation through ion channels. Therefore, we analyze the β -cell activity based on this model [6] in this paper.

Although the dynamics of the membrane potential is mainly determined by the activity of the KATP channels, these channels alone cannot evoke the membrane depolarization. The inward currents through the transient receptor potential melastatin2 (TRPM2) channels are crucial for inducing the membrane depolarization that follows the closure of the KATP channels [1]. The TRPM2 channel is a Ca^{2+} -permeable non-selective cation channel. It has been reported that the TRPM2 channel activation enhances insulin secretion, and prolongs the burst duration of the Ca^{2+} concentration [7].

The dynamics of the membrane potential, including the TRPM2 current, has been expressed using mathematical models [8, 9]. However, the TRPM2 conductance is not a quantitative value, and the prolongment of the burst duration in the TRPM2 channel activation cannot be observed in these models. Therefore, in this paper, we incorporated the TRPM2 current into the mathematical model proposed by Riz et al. [6], and clarified effects of the TRPM2 channel on the membrane potential. Our mathematical analysis reveals the mechanism of enhancing insulin secretion by the TRPM2 channel in pancreatic β -cells. We investigated the reproducibility of the results obtained following the physiological experiments [7]. Furthermore, we revealed the mechanism through which the TRPM2 channel activation enhances the insulin secretion.

2. Methods

The TRPM2 current

The TRPM2 channel is Ca^{2+} -permeable. The relationship between the membrane potential and the TRPM2 current is linear. It is reported that in rat β -cells the TRPM2 channel activation enhances insulin secretion, increases resting potential, and prolongs the duration of Ca^{2+} and inward currents [7]. In [7], if the TRPM2 channel is activated by its activator ex-4, the slope conductance and reversal potential are 0.0823[nS] and -19.2 [mV], respectively; otherwise, they are 0.0252[nS] and -4.4 [mV], respectively. Such tendency that the TRPM2 channel activation induces the increase of TRPM2 channel conductance and the decrease of the reversal potential of the TRPM2 channel is consistent with other study [10]. In this paper, we set several values for the conductance and the reversal potential of the TRPM2 channel to express several levels of TRPM2 activation.

We expressed the TRPM2 current I_{TRPM2} as follows:

$$I_{\text{TRPM2}} = g_{\text{TRPM2}}(V(t) - V_{\text{TRPM2}}), \quad (1)$$

where $V(t)$ is the membrane potential, and g_{TRPM2} and V_{TRPM2} are the TRPM2 conductance and

reversal potential, respectively.

The dynamics of the membrane potential

We incorporated the TRPM2 current shown in Eq. (1) into the model that expresses the dynamics of the membrane potential of a pancreatic β -cell by Riz et al. [6]. The Riz model has a small conductance Ca^{2+} -sensitive K^+ (SK) channel, a large conductance Ca^{2+} -sensitive K^+ (BK) channel, a delayed rectifier K^+ (KV) channel, an ATP-sensitive K^+ (KATP) channel, a Na^+ channel, three voltage-dependent calcium channels, an L-type Ca^{2+} (CaL) channel, a PQ-type Ca^{2+} (CaPQ) channel, a T-type Ca^{2+} (CaT) channel, and a leak channel.

The dynamics of the membrane potential $V(t)$ is expressed as follows:

$$C_m \frac{dV(t)}{dt} = -(I_{\text{KATP}} + I_{\text{SK}} + I_{\text{BK}} + I_{\text{KV}} + I_{\text{Na}} + I_{\text{CaL}} + I_{\text{CaPQ}} + I_{\text{CaT}} + I_{\text{leak}} + I_{\text{TRPM2}}), \quad (2)$$

where C_m is the membrane capacitance, variables I_{KATP} , I_{SK} , I_{BK} , I_{KV} , I_{Na} , I_{CaL} , I_{CaPQ} , I_{CaT} , I_{leak} and I_{TRPM2} are the currents of the KATP, SK, BK, KV, Na, CaL, CaPQ, CaT, leak, and TRPM2 channels.

The KATP channel closes as a result of an increase in the intracellular ATP concentration induced by a glucose metabolism corresponding to the elevation of glucose concentration in the blood. The closure of the KATP channel depolarizes the membrane potential, and triggers the insulin secretion in a pancreatic β -cell. The KATP current I_{KATP} is expressed as follows:

$$I_{\text{KATP}} = g_{\text{KATP}} \frac{1}{1 + [\text{ATP}]} (V(t) - V_K), \quad (3)$$

where $[\text{ATP}]$ is a variable that mimics ATP levels, g_{KATP} is a KATP conductance, and V_K is a reversal potential of the K^+ channel.

The SK channel is one of the Ca^{2+} -activated K^+ channel, and its conductance is small. The SK current I_{SK} is expressed as follows:

$$I_{\text{SK}} = g_{\text{SK}} \frac{[\text{Ca}^{2+}]_m(t)^{5.2}}{K_{\text{SK}}^{5.2} + [\text{Ca}^{2+}]_m(t)^{5.2}} (V(t) - V_K), \quad (4)$$

where g_{SK} is an SK channel conductance, a variable $[\text{Ca}^{2+}]_m(t)$ is a submembrane Ca^{2+} concentration, and K_{SK} is a dissociation constant.

The BK channel is one of the voltage-dependent K^+ channels, it is activated by the Ca^{2+} concentration. Therefore, we incorporated the TRPM2 current I_{TRPM2} into the BK current. The BK current I_{BK} is expressed as follows:

$$I_{\text{BK}} = g_{\text{BK}} m_{\text{BK}} (-I_{\text{CaL}} - I_{\text{CaPQ}} - I_{\text{CaT}} - I_{\text{TRPM2}} + B_{\text{BK}}) (V(t) - V_K), \quad (5)$$

where g_{BK} is a BK conductance, m_{BK} is an activation variable of the BK channel, and B_{BK} is the basal Ca^{2+} -independent activation of the BK channel.

The KV channel is the voltage-dependent K^+ channel. The KV current I_{KV} is expressed as follows:

$$I_{\text{KV}} = g_{\text{KV}} m_{\text{KV}} (V(t) - V_K), \quad (6)$$

where g_{KV} is a KV conductance, and m_{KV} is an activation variable of the KV channel.

The flux of Ca^{2+} through the voltage-dependent Ca^{2+} channels regulates the intracellular signal transductions, such as insulin secretion. The Riz model has three voltage-dependent Ca^{2+} channels: CaL, CaPQ, and CaT. The CaL channel participates in the upstroke of action potential, and increases the excitability of the pancreatic β -cell. The CaL channel has high voltage-dependence and large conductance. The CaL current I_{CaL} is expressed as follows:

$$I_{\text{CaL}} = g_{\text{CaL}} m_{\text{CaL},\infty}(V) h_{\text{CaL}}(V(t) - V_{\text{Ca}}), \quad (7)$$

where g_{CaL} is a CaL conductance, $m_{\text{CaL},\infty}(V)$ is an equilibrium activation variable, h_{CaL} is an inactivation variable, and V_{Ca} is a reversal potential of the Ca^{2+} channel.

The CaPQ channel is highly voltage-dependent, whose inhibition increases the spike frequency. The CaPQ current I_{CaPQ} is expressed as follows:

$$I_{\text{CaPQ}} = g_{\text{CaPQ}} m_{\text{CaPQ},\infty}(V)(V(t) - V_{\text{Ca}}), \quad (8)$$

where g_{CaPQ} is a CaPQ conductance, and $m_{\text{CaPQ},\infty}(V)$ is an equilibrium activation variable.

The CaT channel has low voltage-dependence; it also has small conductance, compared to both the CaL and CaPQ channels. The CaT current, I_{CaT} , is expressed as follows:

$$I_{\text{CaT}} = g_{\text{CaT}} m_{\text{CaT},\infty}(V) h_{\text{CaT}}(V(t) - V_{\text{Ca}}), \quad (9)$$

where g_{CaT} is a CaT conductance, $m_{\text{CaT},\infty}(V)$ is an equilibrium activation variable and h_{CaT} is an inactivation variable.

Blocking the Na^+ channel reduces and prolongs the action potential amplitude. The Na^+ current, I_{Na} , is expressed as follows:

$$I_{\text{Na}} = g_{\text{Na}} m_{\text{Na},\infty}(V) h_{\text{Na}}(V(t) - V_{\text{Na}}), \quad (10)$$

where g_{Na} is a Na conductance, $m_{\text{Na},\infty}(V)$ is an equilibrium activation variable, h_{Na} is an inactivation variable, and V_{Na} is a reversal potential of the Na^+ channel.

The leak channel is always open. The leak current, I_{leak} , is expressed as follows:

$$I_{\text{leak}} = g_{\text{leak}}(V(t) - V_{\text{leak}}), \quad (11)$$

where g_{leak} and V_{leak} are the leak conductance and reversal potential, respectively.

The submembrane Ca^{2+} concentration is changed due to the influx of Ca^{2+} currents. Therefore, we incorporated the TRPM2 current into the dynamics of the submembrane Ca^{2+} concentration. The submembrane Ca^{2+} concentration variable, $[\text{Ca}^{2+}]_{\text{m}}(t)$, and the cytosolic Ca^{2+} concentration variable, $[\text{Ca}^{2+}]_{\text{c}}(t)$, are expressed as follows:

$$\begin{aligned} \frac{d[\text{Ca}^{2+}]_{\text{m}}(t)}{dt} = & f\alpha C_{\text{m}}(-I_{\text{CaL}} - I_{\text{CaPQ}} - I_{\text{CaT}} - I_{\text{TRPM2}})/Vol_{\text{m}} \\ & - f(Vol_{\text{c}}/Vol_{\text{m}})[B([\text{Ca}^{2+}]_{\text{m}}(t) - [\text{Ca}^{2+}]_{\text{c}}(t)) \\ & + J_{\text{PMCA}} + J_{\text{NCX}}], \end{aligned} \quad (12)$$

and

$$\frac{d[\text{Ca}^{2+}]_{\text{c}}(t)}{dt} = f[B([\text{Ca}^{2+}]_{\text{m}}(t) - [\text{Ca}^{2+}]_{\text{c}}(t)) - J_{\text{SERCA}} + J_{\text{leak}}], \quad (13)$$

where f is the free-to-total ratio of the Ca^{2+} concentration, α converts the currents to flux, Vol_{m} and Vol_{c} are the volumes of the submembrane compartment and the bulk cytosol, B describes the Ca^{2+} flux from the submembrane compartment to the bulk cytosol, J_{PMCA} and J_{NCX} are the functions of the flux through the plasma membrane Ca^{2+} -ATPases (PMCA) and Na^+ - Ca^{2+} exchangers (NCX), respectively. In Eq. (13), J_{SERCA} is a function of the sarco/endoplasmic reticulum Ca^{2+} -ATPase (SERCA) pump-dependent sequestration of Ca^{2+} in the endoplasmic reticulum, and J_{leak} is a constant of the leak flux from the endoplasmic reticulum to the cytosol.

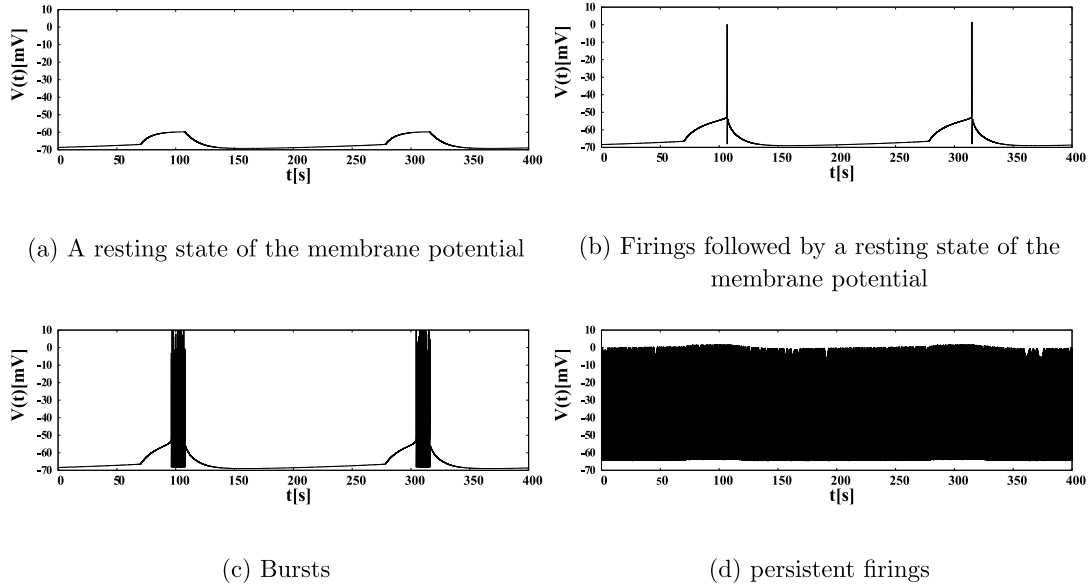
In the original Riz model, there exist two more currents expressing the ligand-gated Cl^- channel current carried by GABA_{A} receptor, and the human ether-a-go-go K^+ -channel current. However, these channel currents are specific to human β -cells. In this paper, we excluded these human-specific currents because our study is based on the experimental results of rat β -cells [7]. Table I shows the parameter values used in the numerical experiments. The undescribed variables and parameter values are the same as that of the Riz model [6].

Table I. Parameter values used in the numerical experiments.

$C_m = 1[\text{pF}]$	$V_K = -75[\text{mV}]$	$g_{\text{KATP}} = 0.13[\text{nS}]$	$g_{\text{SK}} = 0.1[\text{nS}]$
$g_{\text{BK}} = 0.02[\text{nS}]$	$g_{\text{KV}} = 1[\text{nS}]$	$V_{\text{Ca}} = 65[\text{mV}]$	$g_{\text{CaL}} = 0.3[\text{nS}]$
$g_{\text{CaPQ}} = 0.17[\text{nS}]$	$g_{\text{CaT}} = 0.05[\text{nS}]$	$V_{\text{Na}} = 70[\text{mV}]$	$g_{\text{Na}} = 0.4[\text{nS}]$
$V_{\text{leak}} = -30[\text{mV}]$	$g_{\text{leak}} = 0.02[\text{nS}]$	$K_{\text{SK}} = 0.57[\mu\text{M}]$	$f = 0.01$
$\alpha = 5.18 \times 10^{-2}[\mu\text{mol/pA/ms}]$	$\text{Vol}_m = 0.1[\text{pL}]$	$\text{Vol}_c = 1.15[\text{pL}]$	$B = 0.1[\text{ms}^{-1}]$
$J_{\text{leak}} = 0.00094[\mu\text{M/ms}]$			

Firing patterns and definition of bursts

The model reproduces various firing patterns of the membrane potential (Fig. 1). Figure 1(a) reveals that the parameters in Table I, except for $g_{\text{CaL}} = 0[\text{nS}]$ and $g_{\text{TRPM2}} = 0[\text{nS}]$, are consistent with the resting membrane potential. Figure 1(b) shows a firing followed by the resting state of the membrane potential at the parameters in Table I, except $g_{\text{CaL}} = 0.283[\text{nS}]$ and $g_{\text{TRPM2}} = 0[\text{nS}]$. Figure 1(c) shows continuous burst firings at the parameter $g_{\text{TRPM2}} = 0[\text{nS}]$. Figure 1(d) shows that persistent firings by the membrane potential always correspond to the parameters in Table I, excluding $g_{\text{KATP}} = 0.01[\text{nS}]$, $g_{\text{CaL}} = 0.07[\text{nS}]$, and $g_{\text{TRPM2}} = 0[\text{nS}]$. Normal insulin is secreted when there are action potential burst firings [11].

**Fig. 1.** Various firing patterns of the membrane potential.

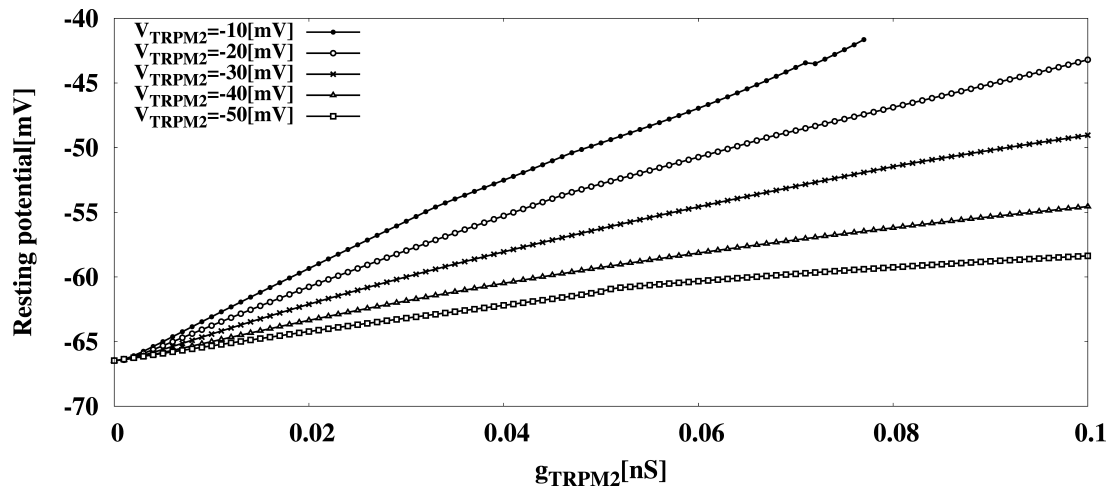
We numerically integrated the differential equations using the Euler method with the step size of $h = 0.01[\text{ms}]$. When t_0 and t_1 were two consecutive times, $t_1 = t_0 + h$. If $V(t_1) - V(t_0) < 0.05$ was maintained for $5[\text{s}]$ or more, and the difference between the maximum and minimum membrane potential was less than $20[\text{mV}]$, we determined that the membrane potential was in a resting state. When the membrane potential was not in a resting state, we determined that it was in an active state. When the active state was maintained for $5[\text{s}]$ or more, we determined it as a burst and its duration is defined as burst duration. Thus, we determined that bursts fired continuously in active states of the membrane potential, and did not fire at all in the resting states.

Using the above-mentioned condition, we investigated the burst duration, because it corresponds to the duration of insulin secretion. A burst duration was defined as the first spike to the last spike in a burst. When the membrane potential was kept in the resting state of the membrane potential (Fig. 1(a)) or a firing followed the resting state of the membrane potential (Fig. 1(b)), the burst duration was 0. In addition, when the membrane potential fired persistently (Fig. 1(d)), the burst duration was equivalent to the observation time.

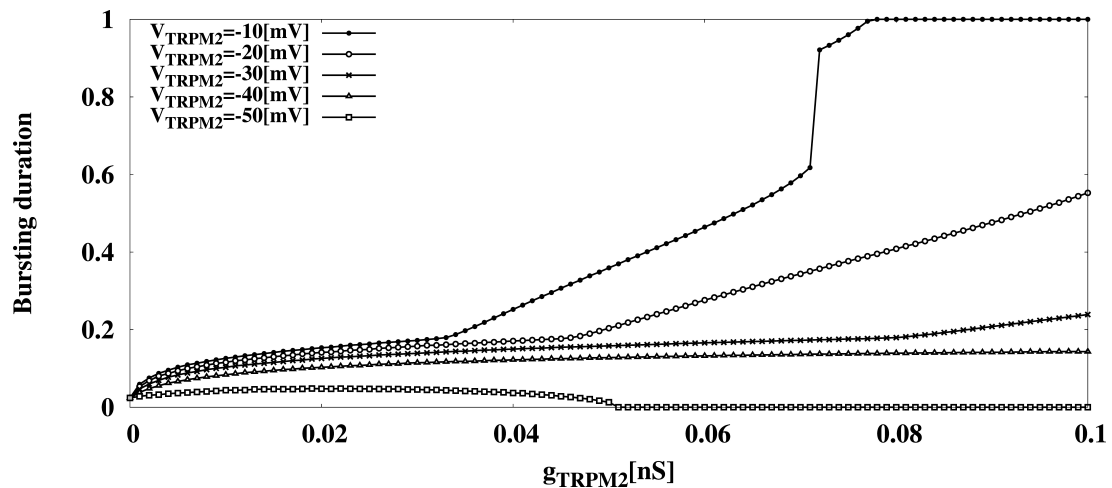
3. Results

Reproducibility of the physiological experiments

The values of the TRPM2 conductance and reversal potential vary for every trial in the physiological experiments [7]. Therefore, we investigated these effects on bursts by varying the TRPM2 conductance and the reversal potential. The TRPM2 activation is represented by the increase in the TRPM2 conductance. In addition, longer bursts correspond to increased insulin secretion. Figure 2 shows the resting membrane potential and burst duration per observation time when the TRPM2 conductance g_{TRPM2} is increased from 0[nS] to 0.1[nS]. These conductance values are quantitatively close to the physiological experiment [7]. In Fig. 2, the lines with filled circles show that $V_{\text{TRPM2}} = -10[\text{mV}]$, lines with open circles show that $V_{\text{TRPM2}} = -20[\text{mV}]$, lines with crosses show that $V_{\text{TRPM2}} = -30[\text{mV}]$, lines with triangles show that $V_{\text{TRPM2}} = -40[\text{mV}]$, and the lines with squares show that $V_{\text{TRPM2}} = -50[\text{mV}]$. When the membrane potential shows no bursts or persistent firings, their durations per observation time are 0 and 1, respectively.



(a) Variations in the resting membrane potential when the TRPM2 conductance is increased.



(b) Variations in the burst duration when the TRPM2 conductance is increased.

Fig. 2. Variations in the resting membrane potential and the burst duration when the TRPM2 conductance is increased. The lines with filled circles show that $V_{\text{TRPM2}} = -10[\text{mV}]$, lines with open circles show that $V_{\text{TRPM2}} = -20[\text{mV}]$, lines with crosses show that $V_{\text{TRPM2}} = -30[\text{mV}]$, lines with triangles show that $V_{\text{TRPM2}} = -40[\text{mV}]$, and lines with squares show that $V_{\text{TRPM2}} = -50[\text{mV}]$.

In Fig. 2(a), the resting potential increases at any reversal potential when the TRPM2 conductance g_{TRPM2} is increased. This result is consistent with the physiological experiments [7]. When $V_{\text{TRPM2}} = -10[\text{mV}]$ (the line with filled circles), the membrane potential fires persistently, corresponding to excessive insulin secretion at $g_{\text{TRPM2}} > 0.077[\text{nS}]$. For the same reason, the line with filled circles peaks at 1 in Fig. 2(b). On the other hand, the line with squares ($V_{\text{TRPM2}} = -50[\text{mV}]$) reaches 0 at $g_{\text{TRPM2}} > 0.051[\text{nS}]$. This corresponds to a lack of insulin secretion.

The physiological experiments [7] show that the TRPM2 activation prolongs the burst duration; the TRPM2 conductance is $0.0823[\text{nS}]$ in the TRPM2 activated state. However, when $V_{\text{TRPM2}} = -40[\text{mV}]$ (the line with triangles), the burst duration is not directly proportional to g_{TRPM2} at $g_{\text{TRPM2}} = 0.0823$. Further, when $V_{\text{TRPM2}} = -30[\text{mV}]$ (the line with crosses), the burst duration does not increase at $g_{\text{TRPM2}} < 0.08[\text{nS}]$. Therefore, it is assumed that the TRPM2 reversal potential is approximately $-20[\text{mV}]$. This value is close to the value obtained in the physiological experiments $-19.2[\text{mV}]$ under the control condition wherein the TRPM2 channel is not activated [7].

As shown above, we confirmed that the TRPM2 reversal potential affects bursts. Here, we investigated the effects of increased TRPM2 conductance g_{TRPM2} on the TRPM2 currents in Figs. 3(a)–(c).

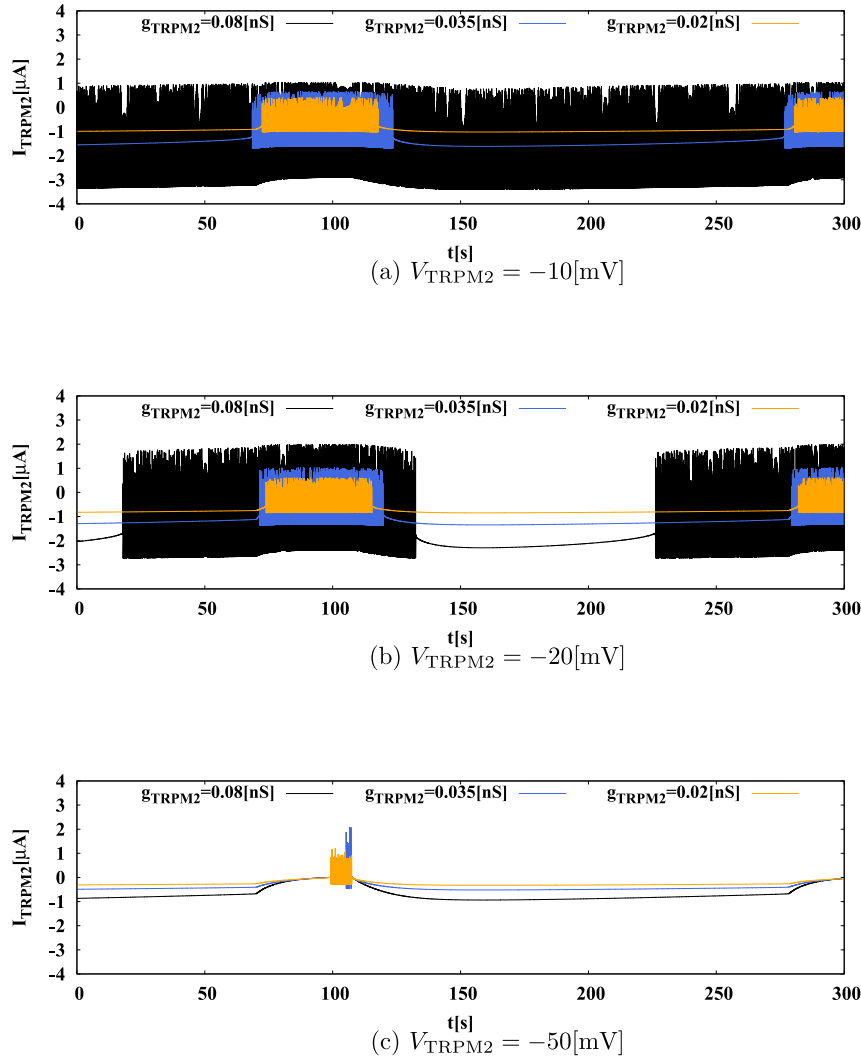


Fig. 3. The TRPM2 currents I_{TRPM2} when the TRPM2 conductance g_{TRPM2} is increased. Orange lines show that $g_{\text{TRPM2}} = 0.02[\text{nS}]$, blue lines show that $g_{\text{TRPM2}} = 0.035[\text{nS}]$, and black lines show that $g_{\text{TRPM2}} = 0.08[\text{nS}]$.

In Fig. 3(a), the burst duration is prolonged, and the influx of the TRPM2 current is directly proportional to the TRPM2 conductance. Increasing the influx of the TRPM2 current increases the membrane potential, and shortens the quiescent duration.

As shown in Fig. 3(b), although the burst duration is long when $V_{\text{TRPM2}} = -20[\text{mV}]$, the TRPM2 currents persistently burst. A comparison of Fig. 3(a) and 3(b) reveals that the influx of the TRPM2 current decreases when the TRPM2 reversal potential is low. This contributes to lengthen the burst duration.

The TRPM2 reversal potential is directly proportional to the influx of the TRPM2 current, and inversely proportional to the efflux. The efflux of the TRPM2 current corresponds to a low membrane potential and firing difficulties. In Fig. 3(c), the relationship between the conductance and bursting duration is reversed compared to Fig. 3(a) and (b), because the low reversal potential $V_{\text{TRPM2}} = -50[\text{mV}]$ induces the efflux of the TRPM2 current increase as the TRPM2 conductance increases.

Effects of TRPM2 channel on Ca^{2+} concentration and channel currents

The results of the TRPM2 reversal potential in our model were consistent with the physiological experiment [7] as shown in the previous section. In this section, we investigated the mechanism underlying enhancing insulin secretion by activating the TRPM2 channel.

The cytosolic Ca^{2+} concentration increases while the membrane potential exhibits bursts [12]; the amount of insulin secretion may be inferred from the amplitude and duration of its concentration. Therefore, the amount of insulin secretion corresponds to its area of concentration.

Figures 4 and 5 show time series of the membrane potential V and the cytosolic Ca^{2+} concentration when the TRPM2 channel is blocked and under the control condition. Figures 4(a) and 5(a) represent time series when the closure of the TRPM2 channel, $g_{\text{TRPM2}} = 0[\text{nS}]$, and the control condition, where $g_{\text{TRPM2}} = 0.0252[\text{nS}]$ [7] in Figs. 4(b) and 5(b). The TRPM2 reversal potential V_{TRPM2} is set to $-20[\text{mV}]$, because the value is optimal for replicating the physiological experiments as shown in the previous section.

Figures 4 and 5 show that the timing of the burst is consistent with the increase in the cytosolic Ca^{2+} concentration, which is consistent with the physiological paper [12]. In Fig. 5, the line under the TRPM2 control condition (Fig. 5(b)) rises faster, and returns more slowly to the resting state

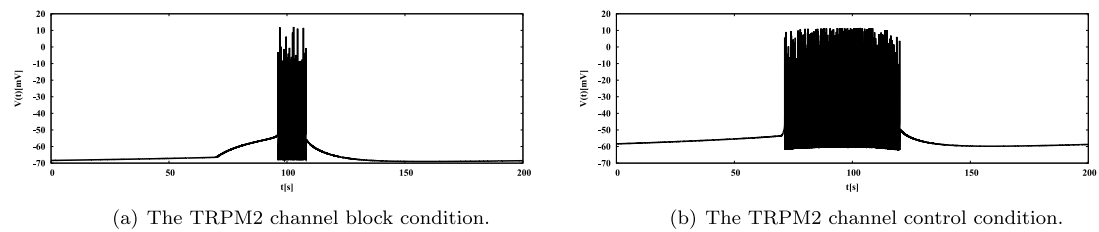


Fig. 4. Time series of the membrane potential under the TRPM2 channel block and control condition. (a) The line denotes that the TRPM2 channel is blocked, i.e., $g_{\text{TRPM2}} = 0[\text{nS}]$. (b) The line denotes the control condition, where the TRPM2 is represented as $g_{\text{TRPM2}} = 0.0252[\text{nS}]$.

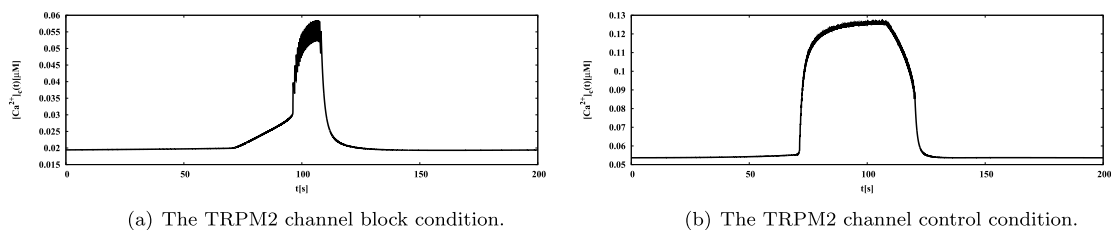


Fig. 5. Time series of the cytosolic Ca^{2+} concentration under the TRPM2 channel block and control condition. (a) The line denotes that the TRPM2 channel is blocked, i.e., $g_{\text{TRPM2}} = 0[\text{nS}]$. (b) The line denotes the control condition, where the TRPM2 is represented as $g_{\text{TRPM2}} = 0.0252[\text{nS}]$.

than the voltage in Fig. 4. In addition, the resting Ca^{2+} concentration rises, and the amplitude increases. These results indicate that insulin secretion can be increased by activating the TRPM2 channel. To compare these results quantitatively, we calculated the area S_1 of the cytosolic Ca^{2+} concentration that represents the amount of insulin secretion in Fig. 6. The area, S_1 , is calculated using $\int_{t_1}^{t_2} ([\text{Ca}^{2+}]_c(t) - [\text{Ca}^{2+}]_{\text{Res}}) dt$, where t_1 and t_2 are the start and end time of the active state and $[\text{Ca}^{2+}]_{\text{Res}}$ is the average resting Ca^{2+} concentration. The resting state of the cytosolic Ca^{2+} concentration is described as when the value of $0.999 < [\text{Ca}^{2+}]_c(t+1)/[\text{Ca}^{2+}]_c(t) < 1.001$ is maintained for 5[s] or more. In addition, the active state is defined as when the cytosolic concentration is not in the resting state. Figure 6 shows that the area of cytosolic concentration under the TRPM2 channel control condition was approximately three times as large as it was when the TRPM2 channel is blocked.

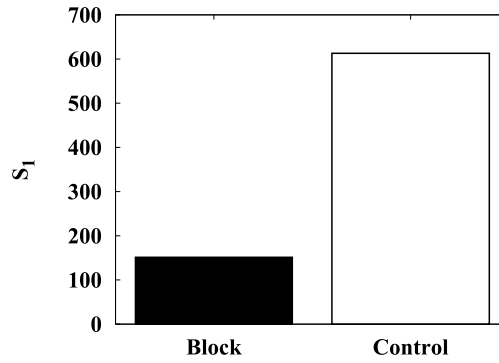


Fig. 6. The areas of $[\text{Ca}^{2+}]_c(t)$ that denote the amount of insulin secretion.

Figure 6 shows that the TRPM2 channel increased the area of the cytosolic Ca^{2+} concentration during insulin secretion. It is also important to investigate whether channels other than the TRPM2 channel regulate insulin secretion. We then calculated the areas S_2 of the currents of the other channels during the active states using $S_2 = \int_{t_1}^{t_2} I(t) dt$, where t_1 and t_2 are the start and end time of the active states, and $I(t)$ is a target channel current. The definition of the active state is the same as that of the membrane potential. In Fig. 7, the black boxes represent the condition under which the TRPM2 channel is blocked, and white boxes represent the control condition. The calculation conditions are the same as in Fig. 4. The outward and inward currents are represented by the rise and fall of the lines, respectively. Figure 7(a) shows the area S_2 of the currents of all the channels, $I(t) = I_{\text{KATP}} + I_{\text{SK}} + I_{\text{BK}} + I_{\text{KV}} + I_{\text{Na}} + I_{\text{CaL}} + I_{\text{CaPQ}} + I_{\text{CaT}} + I_{\text{leak}} + I_{\text{TRPM2}}$. In Fig. 7(b)–7(k), the results obtained from calculating the areas S_2 of the individual channel current. In Fig. 7(b), $I(t) = I_{\text{TRPM2}}$, in Fig. 7(c), $I(t) = I_{\text{CaL}}$, in Fig. 7(d), $I(t) = I_{\text{CaPQ}}$, in Fig. 7(e), $I(t) = I_{\text{CaT}}$, in Fig. 7(f), $I(t) = I_{\text{SK}}$, in Fig. 7(g), $I(t) = I_{\text{BK}}$, in Fig. 7(h), $I(t) = I_{\text{KATP}}$, in Fig. 7(i), $I(t) = I_{\text{KV}}$, in Fig. 7(j), $I(t) = I_{\text{Na}}$ and in Fig. 7(k), $I(t) = I_{\text{leak}}$.

In Fig. 7(a), the inward currents are increased by activating the TRPM2 channel. Increasing the inward currents induces the membrane depolarization to initiate the insulin secretion. In addition, S_2 of each channel current is shown in Fig. 7(b)–(k).

Figure 7(b)–(e) show results obtained from calculating S_2 of Ca^{2+} currents. These currents are negative because of the inward currents. All the inward Ca^{2+} currents increase when the TRPM2 channel is under the control condition. Specifically, activating the TRPM2 channel increases the inward CaL and CaPQ currents (Fig. 7(c) and (d)). This is because the CaL and CaPQ channels are voltage-dependent; thus, these channels are activated when the membrane potential is increased by the activation of the TRPM2 channel. The increases in these inward currents exceed that in the TRPM2 current. This indicates that the TRPM2 channel contributes to enhancing the insulin secretion by increasing the CaL and CaPQ currents.

Figure 7(f)–(i) show the calculation results obtained for S_2 of K^+ currents. These currents are positive, because of the outward currents. All the outward K^+ currents increased when the TRPM2

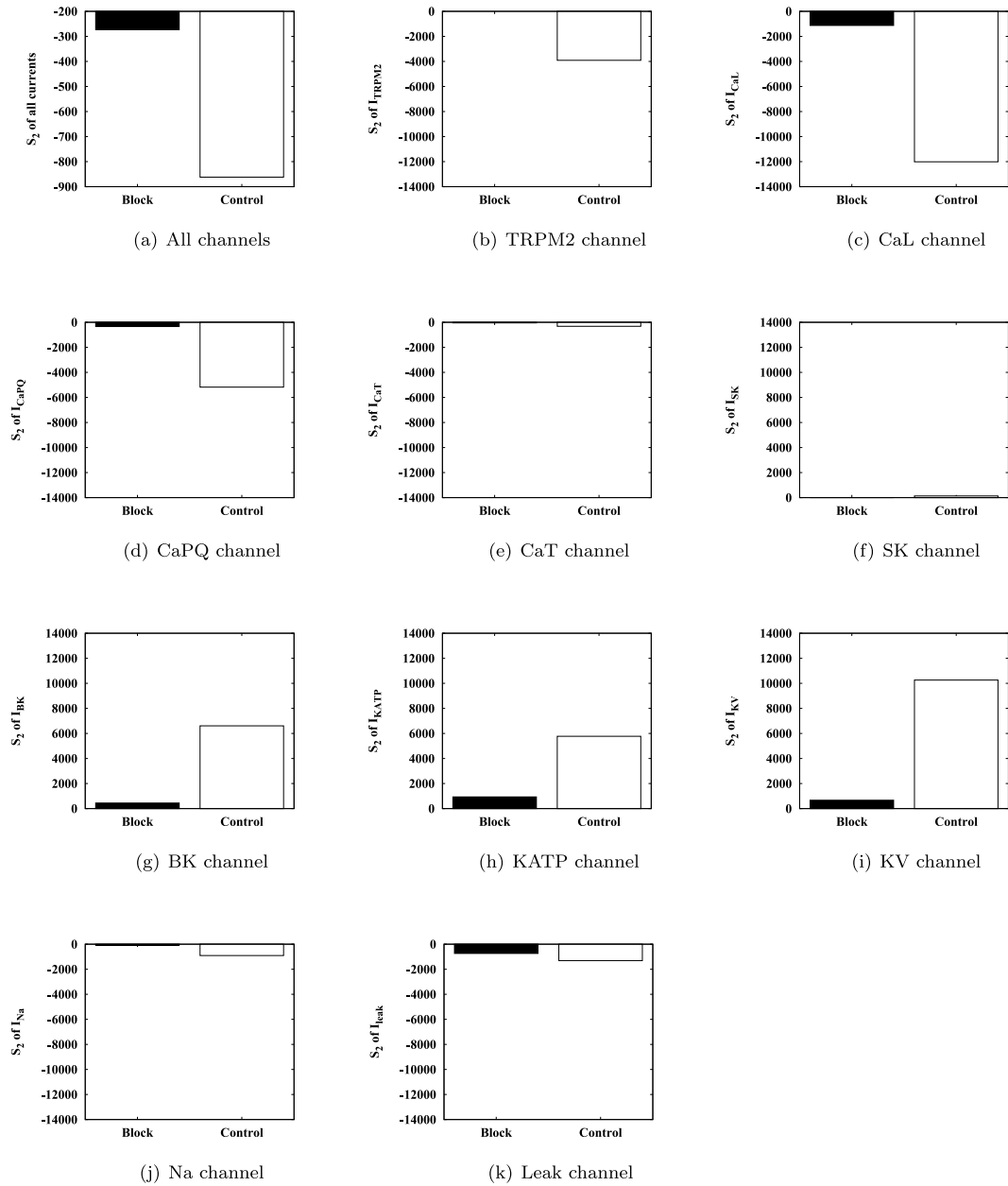


Fig. 7. The areas S_2 of channel currents during the active states. In (a), $I(t) = I_{KATP} + I_{SK} + I_{BK} + I_{KV} + I_{Na} + I_{CaL} + I_{CaPQ} + I_{CaT} + I_{leak} + I_{TRPM2}$, in (b), $I(t) = I_{TRPM2}$, in (c), $I(t) = I_{CaL}$, in (d), $I(t) = I_{CaPQ}$, in (e), $I(t) = I_{CaT}$, in (f), $I(t) = I_{SK}$, in (g), $I(t) = I_{BK}$, in (h), $I(t) = I_{KATP}$, in (i), $I(t) = I_{KV}$, in (j), $I(t) = I_{Na}$, and in (k), $I(t) = I_{leak}$.

channel was under the control condition. The outward KV current, in particular, increased as a result of the TRPM2 channel activation (Fig. 7(i)). This is because the increase in the membrane potential due to the TRPM2 activation activates the voltage-dependent KV channel. Furthermore, the BK channel is activated by the Ca^{2+} currents that are increased by the TRPM2 channel activation. Thus, the outward BK current is increased by the TRPM2 channel activation (Fig. 7(g)).

Figure 7(j) and (k) show the calculation results of S_2 of Na^+ current and leak current. Both inward currents are increased slightly by the TRPM2 channel activation. These results reveal that the TRPM2 channel increases the inward currents. Specifically, the TRPM2 channel activates the

voltage-dependent and Ca^{2+} -sensitive channels with large conductance, and these activation increases the cytosolic Ca^{2+} concentration. This increase in the cytosolic Ca^{2+} concentration leads to the increase of inward currents, then contributes to the membrane activation and prolongment of the burst duration. Consequently, insulin secretion is induced by the TRPM2 channel activation.

4. Conclusion

The activation of the TRPM2 channel has been reported to enhance insulin secretion, and prolong the burst duration in the pancreatic β -cell [7]. In this paper, we incorporated the TRPM2 current into the mathematical model proposed by Riz et al. [6], and investigated the reproducibility of the experimental result [7] and effects of the TRPM2 channel on the membrane potential.

The results of the numerical experiments showed that the activation of the TRPM2 channel prolongs the burst duration when the TRPM2 reversal potential is close to the value observed in the physiological experiments. These results support the relevance of the physiological experiments, and confirm the effects of the TRPM2 channel on insulin secretion. This also indicates that the value of the TRPM2 reversal potential is optimal in terms of efficient insulin secretion.

Furthermore, we investigated the effects of the TRPM2 channel on the other channel's currents. It was revealed that the TRPM2 channel increases the inward currents by activating the voltage-dependent Ca^{2+} -sensitive channels with large conductance; this activation increases the cytosolic Ca^{2+} concentration. These results imply that this is the mechanism through which insulin secretion is increased by the TRPM2 channel activation.

We have constructed a mathematical model including the TRPM2 channel. The effects and relationship between multiple ion channels in the pancreatic β -cells are still physiologically unknown in detail. It is an important future issue to investigate the dynamics of our model by detailed analyses such as a bifurcation analysis.

Pancreas consists of hundred millions of β cells and they are connected via gap-junctional connections. It may be beneficial to construct a network of our proposed model for understanding overall network dynamics of the pancreas. In addition, our theoretical investigation contributes to a new treatment for diabetes by activating TRPM2 channel. There exist several drugs such as calmodulin and ex-4, which are known as a TRPM2 channel activator [13]. Using our model, we can design and control the timing and the duration of drug perturbation for diabetes.

Finally, our model of TRPM2 channel is a simple conductance model, so that it can also be incorporated into neural models. Recently it has been reported that the TRPM2 channel could be a therapeutic target for treating a wide variety of brain diseases, including Alzheimer's disease, neuropathic pain, bipolar disorder, and Parkinson's disease [14]. It would be a future problem to investigate the effects of TRPM2 channel to treatments for such diseases.

Acknowledgments

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References

- [1] M. Kakei, M. Yosida, K. Dezaki, K. Ito, H. Yamada, S. Funazaki, M. Kawakami, H. Sugawara, and T. Yada, "Glucose and GTP-binding protein-coupled receptor cooperatively regulate transient receptor potential-channels to stimulate insulin secretion," *Endocrine Journal*, vol. 63, no. 10, pp. 867–876, 2016.
- [2] M.E. Cerf, "Beta Cell Dysfunction and Insulin Resistance," *Frontiers in Endocrinology*, vol. 4, no. 37, 2013.
- [3] J.C. Florez, "Newly identified loci highlight beta cell dysfunction as a key cause of type 2 diabetes: where are the insulin resistance genes?," *Diabetologia*, vol. 51, no. 7, pp. 1100–1110, 2008.

- [4] T.R. Chay and J. Keizer, “Minimal model for membrane oscillations in the pancreatic beta-cell,” *Biophysical Journal*, vol. 42, no. 2, pp. 181–190, 1983.
- [5] M.G. Pedersen, “A biophysical model of electrical activity in human β -cells,” *Biophysical Journal*, vol. 99, no. 10, pp. 3200–3207, 2010.
- [6] M. Riz, M. Braun, and M.G. Pedersen, “Mathematical modeling of heterogeneous electrophysiological responses in Human β -cells,” *PLoS Computational Biology*, vol. 10, no. 1, p. e1003389, 2014.
- [7] M. Yosida, K. Dezaki, K. Uchida, S. Kadera, N.V. Lam, K. Ito, R.S. Rita, H. Yamada, K. Simomura, S. Isikawa, H. Sugawara, M. Kawakami, M. Tominaga, T. Yada, and M. Kakei, “Involvement of cAMP/EPAC/TRPM2 activation in glucose-and incretin-induced insulin secretion,” *Diabetes*, vol. 63, no. 10, pp. 3394–3403, 2014.
- [8] K. Fujiwara, H. Ando, T. Ikeguchi, M. Yosida, and M. Kakei, “Mathematical model of TRPM2 activation in pancreatic β -cell,” *NOLTA '17*, pp. 387–390, 2017.
- [9] K. Kasahara, Y. Shimada, K. Fujiwara, and T. Ikeguchi, “Reproducing TRPM2 channel activation in pancreatic β -cells using mathematical model,” *Proceedings of the 2018 IEICE General Conference*, N-1-22, 2018.
- [10] C.A. Leech and J.F. Habener, “A role for Ca^{2+} -sensitive nonselective cation channels in regulating the membrane potential of pancreatic beta-cells,” *Diabetes*, vol. 47, no. 7, pp. 1066–1073, 1998.
- [11] H.P. Meissner and H. Schmelz, “Membrane potential of beta-cells in pancreatic islets,” *Pflügers Archiv*, vol. 351, no. 3, pp. 195–206, 1974.
- [12] J. Dolenšek, A. Stožer, M.S. Klemen, E.W. Miller, and M.S. Rupnik, “The relationship between membrane potential and calcium dynamics in glucose-stimulated beta cell syncytium in acute mouse pancreas tissue slices,” *PloS One*, vol. 8, no. 12, p. e82374, 2013.
- [13] Q. Tong, W. Zhang, K. Conrad, K. Mostoller, J.Y. Cheung, B.Z. Peterson, and B.A. Miller, “Regulation of the transient receptor potential channel TRPM2 by the Ca^{2+} sensor calmodulin,” *Journal of Biological Chemistry*, vol. 281, no. 14, pp. 9076–9085, 2006.
- [14] J.C. Belrose and M.F. Jackson, “TRPM2: a candidate therapeutic target for treating neurological diseases,” *Acta Pharmacologica Sinica*, vol. 39, no. 5, pp. 722–732, 2018.

査読あり国際会議

Emotions are hubs in a network of colexification

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Studies on emotions from the viewpoint of languages have been conducted [1]. They classified concepts of emotions by analyzing a network of colexification.

Multiple concepts in polysemous words are related to colexification. For example, a Spanish word “malo” expresses two concepts; “BAD” and “SEVERE.” These concepts are perceived as conceptually similar, colexified by “malo,” and related as colexification. This is the reason why colexifications are useful for addressing issues about semantic structure[2]. To analyze such colexification, we can use CLICS³[3] database, which aggregates colexifications in 208 language families and 3,061 languages[4, 5].

In Ref. [1], networks are created by assigning a concept to a vertex and a colexification to an edge and weights of edges are defined in the created network as the number of languages that colexify two concepts which are connected by an edge. Figure 1 shows how to create a network. In Fig. 1, red lines are colexification, and blue ovals are concepts.

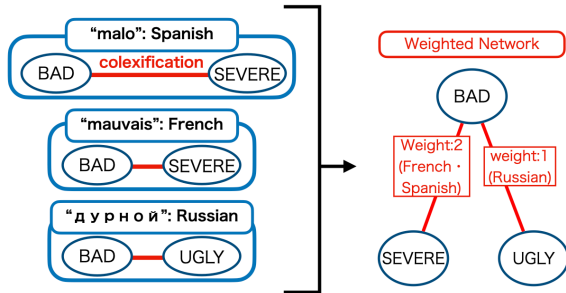


Figure 1: An example of creating a network

In Ref. [1], random walk was applied for a created network to reveal communities of concepts that have many colexification. Random walk is a procedure of moving from one specific node to another specific node through the edges of a network in n steps. Using the random walk, we obtain the transition probability matrix on a network at n steps P^n . In the case of Fig. 1, “SEVERE” and “UGLY” are easy to reach each other through “BAD” by the random walk, then the transition probability between “SEVERE” and “UGLY” is high. Therefore, concepts that are clustered closely together in a network will have high transition probabilities, which reveal communities in a network.

The transition probability matrix at one step ($n = 1$) is defined as $P_{ij} = A_{ij} / \sum_{k=1}^N A_{ik}$ where P_{ij} is the (i, j) th entry of P , A_{ij} is the (i, j) th entry of the weighted adjacency matrix of a network A , and N is the number of vertices.

In Ref. [1], a new weighted adjacency matrix $B^{(n)}$ was defined as $B^{(n)} = \sum_{s=1}^n P^s$. Moreover, a new matrix $B_E^{(n)}$ is defined by choosing only the vertices of 24 typical emotional concepts in $B^{(n)}$. They only analyzed the network of $B_E^{(5)}$ to research a network which has a minimal influence of colexifi-

cation with non-emotional concepts[1]. This is because $n = 5$ is the minimum number of steps that $B_E^{(n)}$ becomes a complete graph. As the result, their network has some similarity-based communities of emotional concepts.

On the other hand, first, we increased the number of steps of the random walk to investigate a network which has a maximum influence of colexification with non-emotional concepts. Next, we defined P_E^n by choosing the vertices of 25 typical emotional concepts by not integrating “HAPPY” and “HAPPINESS” which were integrated as “HAPPY” in Ref. [1]. This is because we create an accurate network from concepts in CLICS³. Finally, we created a new network whose weighted adjacency matrix is P_E^n using language data in CLICS³ to reveal the influence of increasing the number of steps. Figure 2 shows networks of P_E^n at n steps (top). and distributions of weights of edges at n steps (bottom).

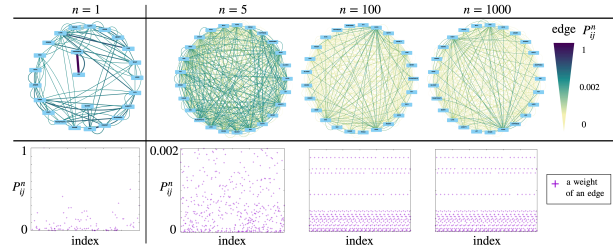


Figure 2: Networks and distributions of weights of edges at step n

Fig. 2 shows qualitatively that weights of edges converge as the number of steps increases. The bottom of Fig. 2 also shows that every edge directed to a vertex has the same weight. Furthermore, the weights of edges directed to specific vertices (“GOOD”, “WANT”, “BAD”, and “LOVE”) were large. Then results indicate that networks increasing the number of steps of the random walk clarified existence of hubs rather than communities.

In this study, we increased the number of steps of the random walk for a network of colexification and analyzed the network. From the results, we show that emotions are hubs in colexification networks.

References

- [1] J. C. Jackson, *et al.*, *Science*, Vol. 366, No. 6472, pp. 1517–1522, 2019.
- [2] A. François, *From Polysemy to Semantic Change: Towards a Typology of Lexical Semantic Associations*, John Benjamins, Philadelphia, pp. 163–215, 2008.
- [3] J. M. List, *et al.*, <https://clics.clld.org/>, (Last visit Dec. 3rd, 2021).
- [4] V. Hoogmartens and J. C. Verstraete, *Australian Journal of Linguistics*, Vol. 40, No. 4, pp. 444–474, 2020.
- [5] F. F. Gerardi, S. Reichert, and C. C. Aragon, *Language Resources and Evaluation*, Vol. 55, No. 4, pp. 997–1015, 2021.

An investigation of basic emotions by colexification network

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Abstract

In studies on emotions from a perspective of natural language processing, an investigation of basic emotions is receiving increased attention. In this study, we investigated the basic emotions from a perspective of colexification of emotional concepts by discovering hubs in a network of colexification. Colexification is a phenomenon in which a word possesses multiple concepts and these concepts tend to be perceived as conceptually connected. A network of colexification is created from colexification in many languages by assigning a concept to a vertex and colexification to an edge. We analyzed a network of colexification consisting of vertices to which concepts of emotions are assigned by defining hubs in this network as basic emotions. As a result, we found four basic emotions: “GOOD,” “WANT,” “BAD,” and “LOVE.”

1. Introduction

Investigations of basic emotions have been conducted from various viewpoints. For example, C. Darwin studied basic emotions from a perspective of evolutionary biology [1]. P. Ekman also analyzed the basic emotions from a perspective of psychology [2].

In recent years, from a perspective of natural language processing, an investigation of emotions using colexification is receiving increased attention [5]. Colexification is a phenomenon in which a word possesses multiple concepts [3]. Multiple concepts which are colexified tend to be perceived as conceptually connected [3, 4]. For example, in Spanish, the word “malo” means two concepts, “bad” and “severe,” and thus these two concepts are colexified each other in Spanish. Then a network of colexification is created by assigning a concept to a vertex and colexification to an edge. In a previous study [5], emotions are classified into several groups by discovering communities in the network of colexification. Although basic emotions have been defined from perspectives of evolutionary biology and psychology [1, 2], the previous study [5] did not discuss basic emotions from the perspective of the network of colexification.

In this study, we identified hubs in a network of colexification consisting of concepts of emotions and their colexifications in various languages. We then defined emotional concepts corresponding to hubs as basic emotions because the concepts corresponding to hubs and many other emotional concepts are colexified, namely conceptually connected with each other, in many languages. As a result, we found that four emotional concepts, “GOOD,” “WANT,” “BAD,” and “LOVE,” are hubs in a network of colexification, and these concepts are basic emotions.

2. How to create a network of colexification

In a network of colexification, vertices represent concepts and two vertices are connected by a weighted edge when their corresponding concepts are colexified in one or more languages. The weights of the edges connecting vertices i and j are denoted by W_{ij} , and W_{ij} is the number of languages in which two concepts corresponding to vertices i and j are colexified. Figure 1 shows an example of creating a network of colexification from concepts “BAD”, “SEVERE”, and “UGLY” which are colexified in Spanish, French, and Russian.

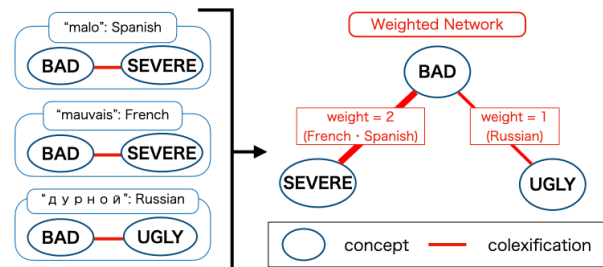


Figure 1: How to create a network of colexification.

In Fig. 1, no edges are drawn between “SEVERE” and “UGLY,” however, both of these concepts and “BAD” are colexified in these three languages. Therefore, “SEVERE” and “UGLY” are also considered to have an indirect connection through colexification associated with “BAD.” To quantify such an indirect relationship and clarify relationships between distant vertices, we apply random walk to a network of colexification.

In our random walk model, random walkers move along edges based on the transition probability matrix $P = (P_{ij})$, where P_{ij} is the probability that a random walker on vertex i moves to vertex j . In a network of colexification with N vertices, P is defined as $P_{ij} = W_{ij} / \sum_{s=1}^N W_{is}$. Then, the transition probability matrix after n steps is P^n in this model.

In the previous study [5], the following procedure was applied to create a network of colexification.

1. Create a network of colexification from data of CLICS³ [4].
2. Calculate a transition probability matrix P^n for $n = 1, \dots, 5$.
3. Generate a network, denoted by $G_{B(n)}$, whose weighted adjacency matrix $B^{(n)}$ is defined by $B^{(n)} = \sum_{s=1}^n P^s$.
4. Create an emotional colexification network $G_{C(n)}$ whose weighted adjacency matrix is $C^{(n)}$ by extracting vertices corresponding to typical emotional concepts and edges connecting them from the network $G_{B(n)}$ (Fig. 2).

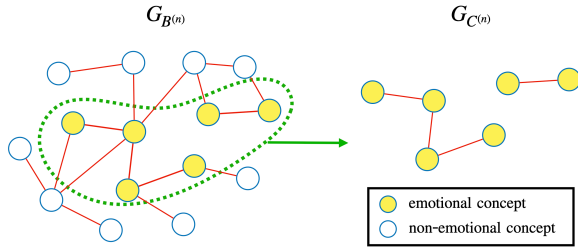


Figure 2: Extracting emotional concepts in a network of colexification.

CLICS³ [4] is a database of colexification in 3,061 languages. Several studies using features of colexification are based on CLICS³ [6, 7]. In CLICS³, concepts are tagged according to their attributes, and emotional concepts are also tagged with “Emotions and values.” In the previous study [5], 24 emotional concepts are selected as typical emotional concepts which are tagged with “Emotions and values” in CLICS³ according to previous studies about emotions [8–17]. Thus, the size of the weighted adjacency matrix $C^{(n)}$ is 24×24 .

When the number of steps in the random walk n is five, the network $G_{C^{(5)}}$ becomes a complete graph for the first time. In other words, the minimum value of n satisfying $C_{ij}^{(n)} > 0$ for any pair of vertices i and j is five. In the previous study [5], emotional concepts are classified into several groups by detecting communities of the emotional colexification network $G_{C^{(5)}}$. However, basic emotions are not taken into account.

3. Methods

In this study, we investigated vertices that are hubs in an emotional colexification network to detect basic emotions from a perspective of colexification. In an unweighted network, a hub is a vertex with a large number of edges. In this study, the emotional colexification network is a directed weighted network, and thus we defined a hub as a vertex whose sum of weights of in-coming edges is large. This is because a weight of an edge in an emotional colexification network is related to the number of languages in which the concepts corresponding to vertices at both ends of the edge are colexified. Then, we created an emotional colexification network and investigated vertices which are hubs.

Let us describe the (i, j) th element of P^n by $\sum_{s_1=1, s_1 \neq i, j}^{N_W} \sum_{s_2=1}^{N_W} \dots \sum_{s_n=1}^{N_W} P_{is_1} P_{s_1 s_2} \dots P_{s_n j}$, which is the probability that a random walker moves from vertex i to vertex j through paths of length $n - 1$. Thus, when $n = 5$, the edge weight between vertices i and j in the network $G_{B^{(n)}}$ reflects the effect of indirect connections through other vertices on paths with length at most $n - 1$. To take into account the effect of long paths between two vertices, we increased the number of steps n in the random walk to 10^3 .

We created an emotional colexification network $G_{Q^{(n)}}$ using the following procedure.

1. Create a network of colexification using data from CLICS³, and defining this network as G_W and the number of vertices in G_W as N_W .
2. Calculate P^n for $n = 10^3$, and generating a directed

weighted network G_{P^n} whose weighted adjacency matrix is P^n .

3. Create a directed weighted network $G_{Q^{(n)}}$ whose weighted adjacency matrix is $Q^{(n)}$ by extracting the vertices corresponding to typical emotional concepts and edges connecting from the network G_{P^n} .

When increasing the number of steps n in the random walk, the values of elements in P^n become small. In the previous study [5], the value of the (i, j) th element of $C^{(n)}$, namely the edge weight, is dominantly determined by the (i, j) th elements of P^n with small values of n . Thus, the values of P^n with large values of n have little influence on the edge weights in a network $G_{C^{(n)}}$. Then, to take into account the values of elements in P^n with large values of n , we create the emotional colexification network $G_{Q^{(n)}}$ from the network G_{P^n} .

We used 25 typical emotional concepts to create an emotional colexification network. In the previous study [5], two concepts “HAPPY” and “HAPPINESS” were treated as a single concept. However, we treated them as distinct concepts because increasing the number of steps in the random walk may detect differences in the vertices assigned to these concepts.

In this study, we investigated weights of edges in the networks $G_{Q^{(n)}}$ as $n = 1, 5, 10^2$, and 10^3 .

4. Results

Distributions of weights of edges in the networks $G_{Q^{(n)}}$ as $n = 1, 5, 10^2$, and 10^3 are shown in Fig. 3.

Figure 3 shows that weights of edges in the emotional colexification networks are likely to converge to a constant value as n increases and edges with the same weights exist in the networks $G_{Q^{(10^2)}}$ and $G_{Q^{(10^3)}}$. We found that all edges with the same weight were directed to the same vertex. We also confirmed that edges with significantly large weights are directed to four vertices: “GOOD,” “WANT,” “BAD,” and “LOVE.” Namely, these four vertices are considered to be hubs in the emotional colexification network.

Then, we defined a strength of in-coming edges of a vertex whose index is i , denoted by $\text{In}_i^{(n)}$, as follows:

$$\text{In}_i^{(n)} = \sum_{j=1, j \neq i}^{N_{Q^{(n)}}} Q_{ij}^{(n)}, \quad (1)$$

where $N_{Q^{(n)}}$ is the number of vertices in $G_{Q^{(n)}}$. We also defined the rank of vertex whose index is i in descending order of $\text{In}_i^{(n)}$, denoted by r_i , and a rate of change in $\text{In}_i^{(n)}$, denoted by θ_i , as follows:

$$\theta_i = \frac{\text{In}_i^{(n)}}{\text{In}_h^{(n)}}, \quad (2)$$

where a vertex h is the vertex whose rank r_h satisfies $r_h = r_i + 1$.

The middle two columns in Table 1 show the values of $\text{In}_i^{(10^3)}$ and θ_i of vertices in the emotional colexification network $G_{Q^{(10^3)}}$.

From Table 1, the four concepts, “GOOD,” “WANT,” “BAD,” and “LOVE” have the largest values of $\text{In}_i^{(10^3)}$ and $\text{In}_i^{(10^3)}$ of “LOVE” is 1.80 times larger than that of “FEAR (FRIGHT).” These results indicate that these four vertices stronger have in-coming weights. Then, we concluded that

these four vertices corresponding to emotional concepts are hubs in the emotional colexification network. We call these four concepts *hub concepts*. Then, we defined these hub concepts as basic emotions from the perspective of colexification.

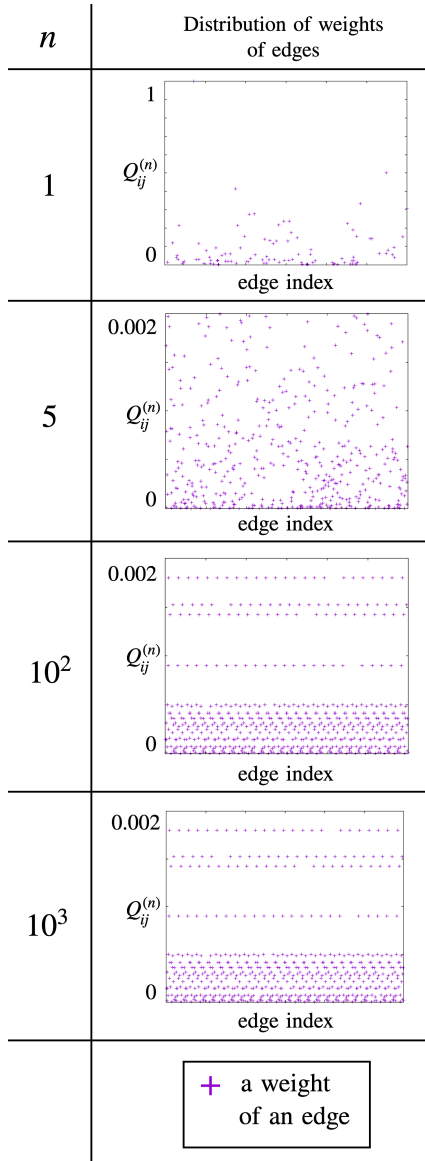


Figure 3: Distributions of weights of edges when $n = 1, 5, 10^2$, and 10^3 .

We also researched relationships between hubs in the emotional colexification network $G_{Q(10^3)}$ and the network of colexification G_W . Then, we generated an unweighted colexification network, defining its adjacent matrix A as follows:

$$A_{ij} = \begin{cases} 1 & (W_{ij} \neq 0) \\ 0 & (W_{ij} = 0) \end{cases}. \quad (3)$$

Using the adjacent matrix A , the degree k_i of vertex i in the network of colexification G_W is defined by

$$k_i = \sum_{j=1}^{N_W} A_{ij}. \quad (4)$$

Moreover, the strength g_i of vertex i in the network of colexification G_W is defined as

$$g_i = \sum_{j=1}^{N_W} W_{ij}. \quad (5)$$

We showed the results of k_i and g_i ($i = 1, \dots, 25$) in the two right columns of Table 1. We then compared the values of $\text{In}_i^{(10^3)}$ with those of k_i and g_i .

Table 1: r_i , $\text{In}_i^{(10^3)}$, and θ_i in the network $G_{Q(10^3)}$, and k_i and g_i in the network G_W .

r_i	vertex	$\text{In}_i^{(10^3)}$	θ_i	k_i	g_i
1	GOOD	4.49×10^{-2}	1.17	126	420
2	WANT	3.81×10^{-2}	1.07	156	356
3	BAD	3.55×10^{-2}	1.57	72	332
4	LOVE	2.25×10^{-2}	1.80	96	211
5	FEAR (FRIGHT)	1.25×10^{-2}	1.03	42	117
6	GRIEF	1.21×10^{-2}	1.16	35	113
7	LIKE	1.04×10^{-2}	1.00	27	97
8	HAPPY	1.03×10^{-2}	1.13	61	97
9	HATE	9.10×10^{-3}	1.01	59	85
10	DESIRE	8.99×10^{-3}	1.13	51	84
11	ANGER	7.92×10^{-3}	1.07	46	74
12	REGRET	7.38×10^{-3}	1.04	31	69
13	HOPE	7.06×10^{-3}	1.13	25	66
14	ANXIETY	6.21×10^{-3}	1.16	19	58
15	SHAME	5.35×10^{-3}	1.31	43	50
16	PITY	4.06×10^{-3}	1.11	13	38
17	ENVY	3.64×10^{-3}	1.00	13	34
18	PROUD	3.64×10^{-3}	1.89	20	34
19	SURPRISED	1.92×10^{-3}	1.12	13	18
20	SAD	1.71×10^{-3}	1.23	9	16
21	HAPPINESS	1.39×10^{-3}	1.85	6	13
22	MERRY	7.49×10^{-4}	1.75	7	7
23	JOY	4.28×10^{-4}	1.33	1	4
24	WORRY	3.21×10^{-4}	3.00	3	3
25	GLOOMY	1.07×10^{-4}		1	1

Focusing on the four hub concepts “GOOD,” “WANT,” “BAD,” and “LOVE” in Table 1, we found that k_i and g_i of these four vertices are higher than those of other vertices, but the rank order of k_i is different from that of g_i : for $\text{In}_i^{(10^3)} < \text{In}_j^{(10^3)}$ at any pairs of vertices (i, j) , g_i always satisfied $g_i < g_j$ but k_i does not satisfy $k_i < k_j$. Therefore, the values of g_i are related to those of $\text{In}_i^{(10^3)}$ of a network of colexification. This implies that hub concepts are likely related to the number of languages in which hub concepts are colexified with other concepts.

5. Conclusion

In this study, we created a network based on colexification and investigated hubs in the network to define basic emotions from a perspective of colexification. We also increased the number of steps in the random walk which is applied to a network of colexification and investigated indirect relationships

between emotional concepts via non-emotional concepts. As a result, we confirmed that the vertices corresponding to the following emotional concepts are hubs: “GOOD,” “WANT,” “BAD,” and “LOVE.” We also found that hub concepts in a network of colexification tend to be colexified with other concepts in many languages. In this sense, these four emotional concepts are basic emotions.

The four basic emotions that we discussed here are different from basic emotions in other fields; C. Darwin gave basic emotions as “SAD,” “HAPPY,” “ANGER,” “CONTEMPT,” “HATE,” “FEAR,” and “SURPRISED”, and P. Ekman gave basic emotions as “ANGER,” “FEAR,” “DISGUST,” “SAD,” and “ENJOY”. Therefore, it implied that the basic emotions from a perspective of colexification are different from those in other fields. However, B. Spinoza gave basic emotions from a perspective of ethics: “PLEASURE,” “SAD,” and “DESIRE” [18]. Although no emotion corresponds to “WANT” in the basic emotions given by C. Darwin and P. Ekman, the basic emotions given by B. Spinoza include the emotion “DESIRE” which may correspond to “WANT” in our case. Therefore, the basic emotions from a perspective of colexification in this study are closely related to the basic emotions defined by B. Spinoza from a perspective of ethics.

References

- [1] C. Darwin, The expression of the emotions in man and animals, *University of Chicago Press*, 2015.
- [2] P. Ekman and D. Lama, Emotional awareness: Overcoming the obstacles to psychological balance and compassion, *Macmillan*, 2008.
- [3] A. François, Semantic maps and the typology of colexification: Intertwining polysemous networks across languages, *From Polysemy to Semantic Change: Towards a Typology of Lexical Semantic Associations*, John Benjamins Publishing, pp. 163–215, 2008.
- [4] J. M. List, *et al.*, The Database of Cross-Linguistic Colexifications, reproducible analysis of cross-linguistic polysemies, <https://clics.clld.org/>. Last visit Dec. 3rd, 2021.
- [5] J. C. Jackson, *et al.*, Emotion semantics show both cultural variation and universal structure, *Science*, Vol. 366, No. 6472, pp. 1517–1522, 2019.
- [6] V. Hoogmartens and J. C. Verstraete, Rations: Flour, sugar, tea, and tobacco in Australian languages, *Australian Journal of Linguistics*, Vol. 40, No. 4, pp. 444–474, 2020.
- [7] F. F. Gerardi, S. Reichert, and C. C. Aragon, TuLeD (Tupían lexical database): introducing a database of a South American language family, *Language Resources and Evaluation*, Vol. 55, No. 4, pp. 997–1015, 2021.
- [8] P. Shaver, J. Schwartz, D. Kirson, and C. O’ Connor, Emotion knowledge: Further exploration of a prototype approach, *Journal of Personality and Social Psychology*, Vol. 52, No. 6, pp. 1061–1086, 1987.
- [9] C. E. Salas, D. Radovic, and O. H. Turnbull, Inside-out: Comparing internally generated and externally generated basic emotions, *Emotion*, Vol. 12, No. 3, pp. 568–578, 2012.
- [10] P. N. Juslin and P. Laukka, Expression, perception, and induction of musical emotions: A review and a questionnaire study of everyday listening, *Journal of New Music Research*, Vol. 33, No. 3, pp. 217–238, 2004.
- [11] N. T. Feather and I. R. McKee, Differentiating emotions in relation to deserved or undeserved outcomes: A retrospective study of real-life events, *Cognition and Emotion*, Vol. 23, No. 5, pp. 955–977, 2009.
- [12] R. L. Morgan and D. Heise, Structure of emotions, *Social Psychology Quarterly*, Vol. 51, No. 1, pp. 19–31, 1988.
- [13] P. M. A. Desmet, Faces of product pleasure: 25 positive emotions in human-product interactions, *International Journal of Design*, Vol. 6, No. 2, pp. 1–29, 2012.
- [14] N. J. MacKinnon and L. J. Keating, The structure of emotions: Canada-United States comparisons, *Social Psychology Quarterly*, Vol. 52, No. 1, pp. 70–83, 1989.
- [15] J. Altarriba and L. M. Bauer, The distinctiveness of emotion concepts: A comparison between emotion, abstract, and concrete words, *The American Journal of Psychology*, Vol. 117, No. 3, pp. 389–410, 2004.
- [16] S. M. Mohammad and P. D. Turney, Crowdsourcing a word–emotion association lexicon, *Computational intelligence*, Vol. 29, No. 3, pp. 436–465, 2013.
- [17] K. C. Berridge, Pleasures of the brain, *Brain and cognition*, Vol. 52, No. 1, pp. 106–128, 2003.
- [18] B. Spinoza, The Ethics: Ethica Ordine Geometrico Demonstrata, *The Floating Press*, 2009.



Relationship between similarities of inter-point distance distributions on attractors and reconstruction parameters

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Abstract—In this study, we investigated the similarities between inter-point distance distributions on original and reconstructed attractors, by varying the reconstruction parameters for reconstructing a dynamical system using a time-delay coordinate system. The results show that the product of the reconstruction dimension and the time-delay should be constant to obtain high similarity.

1. Introduction

The goals of time series analysis include understanding characteristics of systems, generating appropriate models, predicting time series accurately, or controlling systems effectively, from time series data. In particular, understanding the characteristics of systems is of paramount importance. In nonlinear time series analysis, it is known that an attractor of the dynamical system can be reconstructed only from observed time series, even when all the state variables of the system cannot be observed, through a time-delay coordinate system [1, 2]. When using the time-delay coordinate system, attractors cannot be properly reconstructed if we fail to set appropriate reconstruction parameter values. In particular, it is not easy to set appropriate reconstruction parameters when finite data length is only available as in the real world. If the attractor is reconstructed with appropriate parameter values, the reconstructed attractor is expected to be similar in geometric structure to the original attractor. The geometric structure of the attractor is closely related to the fractal dimension, and a method of estimating the fractal dimension using the inter-point distance distribution on an attractor has been proposed [3]. Thus, this paper focuses on the inter-point distance distribution on the attractor as a geometric feature and investigates the dissimilarity between the inter-point distance distributions on attractors using the Jensen–Shannon (JS) divergence [4].

2. Evaluation procedures and methods

In this study, the Lorenz equations [5] are used as an example of a chaotic dynamical system. First, we normalize the three variables x_t , y_t and z_t of the Lorenz equations to the range [0, 1]. For example, the variable x_t is normalized by $\hat{x}_t = (x_t - x_{\min}) / (x_{\max} - x_{\min})$, where $\hat{x}_t$ is the normalized x_t and $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of x_t . The variables y_t and z_t are normalized in the same manner. We define a point at time t on the normalized Lorenz attractor as $\mathbf{v}(t) = (\hat{x}_t, \hat{y}_t, \hat{z}_t)$. Then, we transform the normalized time series $\hat{x}_t$ into the time-delay coordinate system: $\mathbf{x}(t) = (\hat{x}_t, \hat{x}_{t+\tau}, \dots, \hat{x}_{t+(m-1)\tau})$, where m is the reconstruction dimension and τ is the time-delay. Let $d_{\mathbf{v}}(i, j)$ be the inter-point distance between points $\mathbf{v}(i)$ and

$\mathbf{v}(j)$ on the normalized original attractor, and $d_{\mathbf{x}}(i, j)$ be the inter-point distance between points $\mathbf{x}(i)$ and $\mathbf{x}(j)$ on the normalized reconstructed attractor. We calculated $d_{\mathbf{v}}(i, j)$ and $d_{\mathbf{x}}(i, j)$ for every pair i and j and normalized the distances such that the mean and variance of the distances would be zero and unity. Then, we generate the inter-point distance distributions $P_{\mathbf{v}}$ and $P_{\mathbf{x}}$ from the normalized inter-point distances. Finally, we calculate the JS divergence $D_{\text{JS}}(P_{\mathbf{v}}, P_{\mathbf{x}})$ between inter-point distance distributions $P_{\mathbf{v}}$ and $P_{\mathbf{x}}$. The same procedure is applied to the variables y and z to calculate $D_{\text{JS}}(P_{\mathbf{v}}, P_{\mathbf{y}})$ and $D_{\text{JS}}(P_{\mathbf{v}}, P_{\mathbf{z}})$.

3. Numerical experiments

We calculated the JS divergence when the reconstruction dimension m and the time-delay τ were varied in the range of $1 \leq m \leq 20$ and $1 \leq \tau \leq 20$. The Lorenz equations were solved using the fourth order Runge-Kutta method with a step size of 0.01. We used 5,000 data points after removing 100,000 data points as transient states. The result for the variable x_t is shown in Fig. 1.

Figure 1 shows that as the reconstruction dimension increases, the JS divergence is minimized with a small time-delay. By contrast, as the reconstruction dimension decreases, the JS divergence is minimized with a large time-delay. This is because the trajectories on attractors

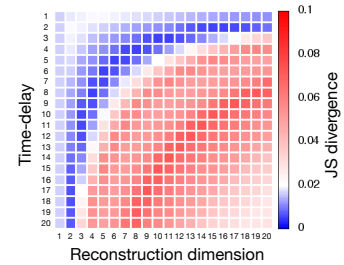


Figure 1: JS divergence between inter-point distance distributions of the original and reconstructed Lorenz attractors (variable x).

unfolded even in low dimensions when the time-delay is large. This result reveals that the reconstruction parameter values that minimize the JS divergence followed a curve where the products of the reconstruction dimension m and the time-delay τ are constant.

This research is partially supported by JSPS KAKENHI Grant Numbers JP17K00348, JP20H00596, JP21H03508, and JP21H03514.

References

- [1] Takens, in *Dynamical Systems and Turbulence*, Warwick 1980, 366–381, Springer, 1981.
- [2] Sauer et al., *J. Stat. Phys.*, **65**(3):579–616, 1991.
- [3] Grassberger et al., *Phys. Rev. Lett.*, **50**(5):346–349, 1983.
- [4] Lin, *IEEE Trans. Inf. Theory*, **37**(1):145–151, 1991.
- [5] Lorenz, *J. Atmos. Sci.*, **20**(2):130–141, 1963.



Statistical analysis on usage history of bike sharing systems

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Abstract—In this study, we investigated how the event generation of bicycles rented and returned in a bike sharing system behaves using real usage history data as a point process. As a result, it is suggested that the event generation of bicycles rented and returned follows a Poisson process when we restricted the usage history to working days from 8:00-20:59.

1. Introduction

In bike sharing system (BSSs), when many bicycles are used, the number of bicycles at each port becomes unbalanced. To overcome this problem, capacitated vehicles need to relocate the bicycles at each port. Thus, we have already proposed a method for finding optimal tours of vehicles in short time [1]. To investigate the performance of the proposed method [1], we generated original benchmark instances with randomly placed ports in the numerical experiments. However, it is important to build realistic benchmark instances from actual usage history of rented and returned bicycles to realize effective strategies for rebalancing bicycles in real BSSs. Thus, in this study, we conducted statistical analysis of usage history data of bicycles of four BSSs (Boston, Washington D.C., New York and Chicago).

2. Statistical Analysis

To analyze how the temporal patterns of events of rented and returned bicycles at each port behave, we treat the usage history data as a point process in this study. The data include time stamps when a bicycle was rented and returned with the IDs of ports. Then, we defined the generation of an event as the time when a bicycle is rented or returned. We analyzed two point processes, rented and returned, separately. To analyze these point process data, we used raster plots and coefficient of variation (CV).

In this article, we only show results of New York BSS [2]. Figure 1 shows the raster plot of rented bicycles in New York from 1st to 7th August 2019. The horizontal axis shows time in minutes and the vertical axis shows the port ID (the total number of ports is 794). From Fig. 1, we can see a periodic pattern, which indicates that many bicycles are used during the daytime and few bicycles are used during the midnight.

Next, we calculate inter event interval (IEI) from rental and return timings. Using the IEI, we calculated coefficient of variation, $CV = \sigma/\bar{x}$, where σ is the standard deviation of IEI and $\bar{x}$ is the mean of IEI. If $CV = 0$, IEI is regular, and if $CV = 1$, IEI follows the Poisson process. Figure 2 shows a result of CV of rented bicycles on August 2019 in New York. The horizontal axis shows the port ID and the vertical axis shows the CV values. In Fig. 2, the red line shows CV of rented bicycles using all the data (31 days) of August 2019. If we use all the data of August 2019, the CV value is larger than unity. From Fig. 1, users rarely rent a

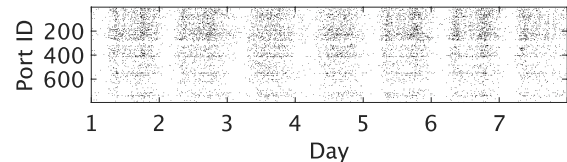


Figure 1: Raster plot representation of timings of rented bicycles of New York. The black points represent that the bicycles are rented.

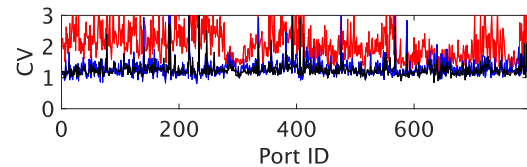


Figure 2: CV values of rented and returned bicycles on August 2019 in New York. We have removed ports which have only one IEI.

bicycle at midnight. Then, we calculated the CV values by removing events from 21:00-7:59 and weekends. In these cases, we used the edge-connecting method (CN) [3] to obtain the IEI. The black line shows CV of rented bicycles calculated from IEI of working days from 8:00-20:59. The blue line shows CV of returned bicycles calculated from IEI of working days from 8:00-20:59. As a result, the CV values take values near to unity at almost ports. These results indicate that events generation of bicycles rented and returned follow the Poisson process.

3. Conclusion

In this study, to determine how the temporal patterns of rented and returned bicycles of BSSs exhibit, we used a raster plot and the coefficient of variation to analyze real usage history of BSSs. From the result of raster plot, we can see a periodic pattern, which indicates that many bicycles are used during the daytime and few bicycles are used during the midnight. Then, from the results of the coefficient of variation, it is suggested that the temporal patterns of bicycles rented and returned of working days from 8:00-20:59 follow a Poisson process. This research is partially supported by the JSPS Grant-in-Aids for Scientific Research (No. JP20H000596 and JP21H03514).

References

- [1] H. Tsushima et al., *App. Sci.*, 11(16), 7749, 2021.
- [2] Citi Bike. <https://www.citibikenyc.com/system-data>.
- [3] K. Fujiwara et al., *NOLTA, IEICE*, 6(1), 38–46, 2015.



Analysis of the Influence of Contact Order on Information Diffusion by Surrogate Temporal Networks

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Abstract—In recent years, information diffusion on static networks is well discussed. We have already reported that the contact order of vertices with high eigenvector centralities affects information diffusion on the temporal networks. In this paper, in addition to the eigenvector centrality, we introduced closeness and betweenness centralities and defined a synthetic centrality by integrating these three centralities. We then investigated the relationship between the contact order of vertices with high synthetic centralities and information diffusion on temporal networks. As a result, we found that if contacts with high synthetic centralities occurs more frequently in the early term, the information spreads more widely in case that the information is influential and the decay of interest is strong.

1. Introduction

Many researches on information diffusion have been reported. These researches are mainly applied to static networks [1–3]. However, the real world is not static but dynamic, which means that we have to analyze not only static networks but also temporal networks (TN) whose structure changes dynamically. We have already reported that the contact order of vertices with high eigenvector centralities affect information diffusion on the TNs [3]. However, many centralities other than the eigenvector centrality can also be important measures on information diffusion. In this paper, we define a synthetic centrality as the average of three centralities: eigenvector, closeness, and betweenness centralities. We then hypothesize that if contacts of vertices with high synthetic centralities occur more frequently in the early term or late term of information diffusion, the information spreads more widely. To validate this hypothesis, we produce surrogate networks that have high synthetic centralities in the early term or the late term, and compared the final diffusion rates of the original network and those of surrogate networks.

2. Numerical Experiments

We obtain TNs by transforming a face-to-face contact data sets taken at a high school in France [4, 5]. Let us describe the (i, j) th component of the adjacency matrix of the TNs at time t as $A_{ij}(t)$. If there is a contact between two vertices (people) i and j at time t , $A_{ij}(t) = A_{ji}(t) = 1$, otherwise $A_{ij}(t) = A_{ji}(t) = 0$. These contacts are recorded every 20 seconds. Then, we use the model of information diffusion proposed in Ref. [3]. We define the interest level on information of vertex i as $x_i(t)$. It follows: $x_i(t+1) = g_i(\tau, t)x_i(t) + \alpha H(x_i(t) - \theta_i) \sum_{j \in G_i(t)} F(x_j(t) - \theta_j)$, where

$F(x)$ is the step function; $G_i(t)$ is the set of adjacent vertices of vertex i at time t ; θ_i is the threshold of vertex i and follows a truncated normal distribution with an average $\mu = 0.5$ and a variance $\sigma^2 = 0.04$ which lies within the range $[0, 1]$; α is the influence of information; $g_i(\tau, t) = \tau$, if $t - t_i^* \equiv 0 \pmod{3600}$, otherwise $g_i(\tau, t) = 1$ and t_i^* is the timing when vertex i first receives the information; τ ($\tau < 1$) is a decay coefficient; and $H(x) = 0$, if $x \geq 0$, otherwise $H(x) = 1$.

Next, we define a synthetic centrality of vertex i as $Z_i = (E_i + C_i + B_i)/3$, where E_i is the eigenvector centrality [6], C_i is the closeness centrality [7], and B_i is the betweenness centrality [8] of vertex i . Note that we calculated E_i , C_i and B_i on the static network in which all contacts are merged. We normalized them [6–8] in the range of $[0, 1]$. We define the synthetic centrality of contact (i, j) as $Z_{ij}^{\max} = \max\{Z_i, Z_j\}$. Then, we define contacts with high $Z_{ij}^{\max}$ as influential contacts in information diffusion, because these contacts include vertices with high $Z_{ij}^{\max}$ which can play an important role in information diffusion. To make surrogate networks, we sort all contacts except the first contact in the descending order or the ascending order. We define the final diffusion rate S as the fraction of the number of vertices whose interest level reaches the threshold once before the diffusion ends. Subsequently, we evaluate S using the proposed model on the original TN and its surrogate networks by changing α when $\tau = 0.95$ and 0.99 . We define the first contact as (i^*, j^*) and set the initial interest level of vertex i^* as $x_{i^*}(0) = 1$ to start the diffusion. The results are shown in Fig. 1.

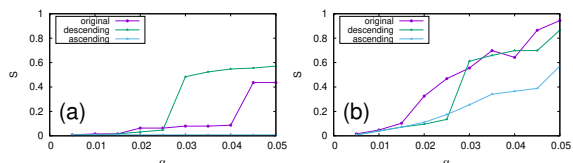


Figure 1: Relationship between α and S on the original TNs and their surrogate networks. (a) $\tau = 0.95$ and (b) $\tau = 0.99$.

From Fig. 1, we found that S obtained from the surrogate networks whose contacts are sorted in descending order is higher than that of the original TN, where $\alpha \geq 0.03$ and $\tau = 0.95$.

3. Conclusion

In this paper, to investigate how network centralities of vertices on a temporal network affect the information diffusion, we compared the final diffusion rate of the original temporal network and its surrogate networks. The results suggest that if contacts are sorted in the descending order of the synthetic centrality, the information spreads more widely, if the information is influential ($\alpha \geq 0.03$) and the decay of interest is strong ($\tau = 0.95$). This research is partially supported by the JSPS Grant-in-Aids for Scientific Research (Nos. JP17K00348, JP20H00596, JP21H03508 and JP21H03514).

References

- [1] D. J. Watts & S. H. Strogatz, *Nature*, **393**, 440–442, 1998.
- [2] D. Centola, *Science*, **329**, 1194–1197, 2010.
- [3] Luyan Xu et al., *Proc. of NCSP'21*, 73–76, 2021.
- [4] <http://www.sociopatterns.org/> (Accessed: 2021/09/01)
- [5] J. Fournet & A. Barrat, *PLOS ONE*, **9**, e107878, 2014.
- [6] P. Bonacich, *Journal of Mathematical Sociology*, **2**, 113–120, 1972.
- [7] A. Bavelas, *The Journal of the Acoustical Society of America*, **22**, 725–730, 1950.
- [8] L. Freeman, *Sociometry*, **40**, 35–41, 1977.



Investigation of Structural Features of Word Co-occurrence Network with Varying the Number of Connected Words

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Abstract—Recent researches on languages based on complex network theory have revealed structural features of various word co-occurrence networks (WCNs) created from text documents written in different languages. The WCN consists of vertices that correspond to words (morphemes) and edges that connect n consecutive words in a sentence, based on n -gram. Most of researches used WCNs transformed with $n = 2$ (bigram). However, it is not sufficient to investigate structural features of the WCNs only in case that $n = 2$. In this study, we investigated structural features of WCNs created from the New Testament of the Christian Bible for nine languages, when n is increased. The result shows that language analysis with WCNs created as n increases is an essential way to reveal structural features of multiple languages.

1. Introduction

There are about 6,800 different languages in the world, and various studies have been conducted. Recent researches on word co-occurrence networks (WCNs) have revealed commonalities and differences in their structures among multiple languages [1]–[3]. In WCN, n consecutive words are connected to each other. We have already investigated the structural features of WCNs transformed from the New Testament of the Christian Bible [4] when $n = 2$ (bigram). However, there is an issue that WCNs can cover only a part of syntactic dependency relations [5] if $n = 2$. Therefore, in this study, we investigated structural features of three different WCNs constructed by connecting n consecutive words ($n = 2, 3, 4$), namely, bigram, trigram and quadrigram.

2. Method for transforming documents into word co-occurrence networks

We used the New Testament of the Christian Bible translated into nine languages [4]. The reasons why we used these documents are two folds: (i) the content of these documents is the same, and (ii) these documents are translated into many different languages. First, we applied a morphological analysis to the documents to divide a sentence into a prototype of words and obtained their part-of-speech (PoS). Then, we treated the pair of the prototype and its PoS as a vertex. Next, we created unweighted and undirected WCNs with $n = 2, 3$ and 4. In WCN, n vertices are connected with each other if their corresponding words are consecutive in at least one sentence. Note that the duplication of words or connections between words are not allowed, and symbols are excluded. Figure 1 shows an example of transforming the documents into WCN. In Fig. 1, the upper part of the vertices expresses a prototype of the word, and the lower part of the vertices expresses the PoS tag [6].

3. Results

We calculated the clustering coefficient (C) [7] and the average path length (L) [7] of WCNs. Figure 2 shows the results of the relation between C and L for the WCNs.

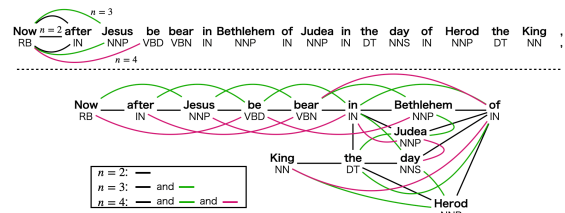


Figure 1: An example of transforming documents into WCNs.

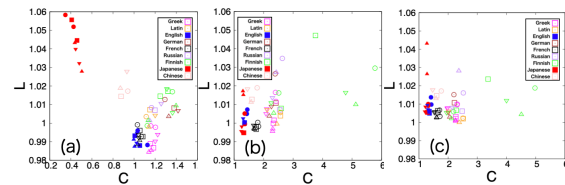


Figure 2: Relation between C and L . (a) $n = 2$, (b) $n = 3$ and (c) $n = 4$. $\square$, $\circ$, $\triangle$ and ∇ express the Gospels of Matthew, Mark, Luke and John, respectively.

In Fig. 2(a) and (b), the values of C increase for all languages when n increases from $n = 2$ to $n = 3$. However, the values of C remain almost unchanged when n increases from $n = 3$ to $n = 4$ in Fig. 2(b) and (c). On the other hand, the values of L approach unity for all languages as n increases in Fig. 2, because words that are not connected when $n = 2$ are connected as n increases. As a result, the number of shortcuts in the WCNs increases. In addition, Fig. 2 shows that the increasing rates of C and L vary across languages as n increases. For example, from Fig. 2(a) and (b), we can see that the value of C of Japanese (red) increases from 0.4 to 1.2 and the value of L increases from 1.04 to 1.0. The increasing rate of C in Japanese is 3.0 and that of L is 0.96. On the other hand, the value of C of English (blue) increases from 1.0 to 1.2 and the value of L increases from 0.99 to 1.0. The increasing rate of C in English is 1.2 and that of L is 1.01. Therefore, we could reveal hidden structural features of WCNs by using the increasing rates of C and L as n increases.

4. Conclusion

In this study, we constructed WCNs by connecting n consecutive words and analyzed structural features of the WCNs by increasing n . As a result, we found that the structural features of the WCNs changed differently as n increases, depending on the language.

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References

- [1] C. I. R. Ferrer *et al.*, *Biol. Sci.*, **268**, 1482, 2261, 2001.
- [2] Y. Shimada *et al.*, *EPL*, **127**, 5, 56003, 2019.
- [3] G. Yuyang *et al.*, *Phys. A*, **393**, 579–589, 2014.
- [4] K. Magishi *et al.*, *Society Conf. IEICE*, N-1-14, 2020.
- [5] C. I. R. Ferrer *et al.*, *PRE*, **69**, 5, 051915, 2004.
- [6] <https://www.cis.lmu.de/~schmid/tools/TreeTagger/> (2021-08-26)
- [7] D. J. Watts, *et al.*, *Nature*, **393**, 440–442, 1998.



Non-Periodic Responses of the Izhikevich Neuron Model with Periodic Inputs

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Abstract—It is widely acknowledged that neurons show irregular responses with periodic inputs. In this study, we numerically analyzed responses of the Izhikevich neuron model to sinusoidal inputs. Evaluating the diversity index of inter spike intervals (ISIs), we discovered that sinusoidal inputs can produce irregular responses of the Izhikevich neuron model.

1. Introduction

It is experimentally shown that real neurons exhibit irregular responses such as chaotic responses or quasi-periodic responses under periodic stimuli such as sinusoidal inputs [1][2]. In Ref. [3], responses of the Izhikevich neuron model [4] to sinusoidal inputs were studied and various mode-locked states were observed. In this study, we used the Izhikevich neuron model with a parameter set of a regular spiking (RS) neuron and analyzed whether sinusoidal inputs can produce non-periodic responses.

2. Experiments

In this study, the Izhikevich neuron model were stimulated by a periodic input current defined as $I(t) = I_{DC} + I_{AC} = I_{DC} + A \sin(2\pi/T)t$, where I_{DC} is a constant part and I_{AC} is a periodic part. We set $I_{DC} = 10$ and changed the amplitude A in a range of $0 \leq A \leq 10$ and the period T in a range of $1 \leq T \leq 2000$.

To evaluate the response of the Izhikevich neuron model, we used the diversity index of inter spike intervals (ISIs), which is defined as $R = m/n$ [5], where m and n represent the number of the kinds of ISIs and the total number of ISIs, respectively. In this study, if the i th and the j th ISIs are equal to two decimal places, these ISIs are defined to be the same. Then, $R \rightarrow 0$ means a periodic response and $R \rightarrow 1$ implies an irregular, possibly a chaotic response.

Figure 1 shows the diversity indices of ISIs by changing the amplitude and the period of the sinusoidal inputs. The color bar represents the diversity index of ISIs. In Fig. 1, the region where the diversity indices are close to zero corresponds to periodic responses and the region where the diversity indices are close to unity corresponds to irregular responses. When the period T is relatively small, amplitudes less than six can result in periodic responses. However, as T increases, the boundary between periodic responses and irregular responses in Fig. 1 converges to the amplitude $A = 6$.

Figure 2 shows an example of trajectories of the model. Figure 2(a) corresponds to a periodic response and Fig. 2(b) corresponds to an irregular response. In Fig. 2(a), when A is greater than six, the v -nullcline intersects with the u -nullcline if the sinusoidal input takes the minimum value ($I(t) = I_{DC} - A$). In contrast, in Fig. 2(b), when A is less than six, the v -nullcline does not intersect with the u -nullcline. When the amplitude $A = 6$, the v -nullcline is tangent to the u -nullcline at the minimum value of $I(t)$.

These characteristics could play a crucial role in producing irregular responses of the Izhikevich neuron model stimulated by the sinusoidal inputs.

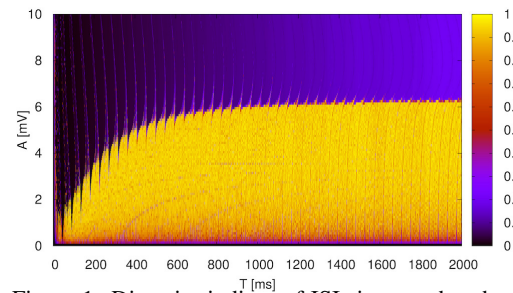


Figure 1: Diversity indices of ISIs in case that the amplitude A and period T changed.

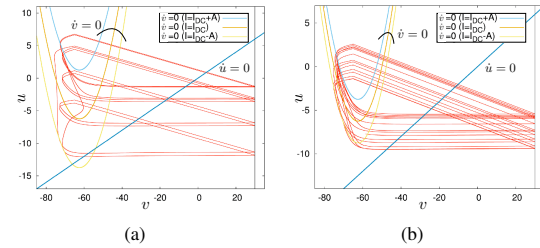


Figure 2: Trajectories induced by the sinusoidal inputs of (a) a 9-period response ($A = 7.5$, $T = 200$) and (b) an irregular response ($A = 2.5$, $T = 200$).

3. Conclusion

In this study, we evaluated responses of the Izhikevich neuron model with sinusoidal inputs by the diversity index of ISIs. As a result of numerical experiments, even if the parameters of the Izhikevich neuron model is set to RS parameters, irregular responses can be observed if the two nullclines do not intersect. The diversity index of ISIs is a simple method for distinguishing periodic responses and irregular responses. Therefore, one of the important future issues is to determine whether irregular responses are chaotic or not in a rigorous way. This research is partially supported by the JSPS Grant-in-Aids for Scientific Research (No. JP17K00348, JP20H000596 and JP21H03514).

References

- [1] Hayashi et al., *PLA*, 88(8), 435–438, 1982.
- [2] Aihara et al., *PLA*, 116(7), 313–317, 1986.
- [3] Farokhniaee et al., *PRE*, 95(6), 062414, 2017.
- [4] Izhikevich, *IEEE TNN*, 14(6), 1569–1572, 2003.
- [5] Sugiura et al., *IEICE Tech. Rep.*, NLP2013-34, 2013.

Dynamical Characteristics of Wild-Type Mouse Spontaneous Pupillary Fluctuations*

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Abstract— Spontaneous pupil size fluctuations in humans and mouse models are noninvasively measured data that can be used for early detection of neurodevelopmental spectrum disorders. While highly valuable in such applied studies, pupillometry dynamics and dynamical characteristics have not been fully investigated, although their understanding may potentially lead to the discovery of new information, which cannot be readily uncovered by conventional methods. Properties of pupillometry dynamics, such as determinism, were previously investigated for healthy human subjects; however, the dynamical characteristics of pupillometry data in mouse models, and whether they are similar to those of human subjects, remain largely unknown. Therefore, it is necessary to establish a thorough understanding of the dynamical properties of mouse pupillometry dynamics and to clarify whether it is similar to that of humans. In this study, dynamical pupillometry characteristics from 115 wild-type mouse datasets were investigated by methods of nonlinear time series analysis. Results clearly demonstrated a strong underlying determinism in the investigated data. Additionally, the data's trajectory divergence rate and predictability were estimated.

I. INTRODUCTION

Spontaneous pupil size fluctuations are controlled by the autonomous nervous system. Even under constant conditions pupil size fluctuates and produces complex, seemingly random dynamics [1,2]. Pupil size fluctuations can be used to track changes in mental states and behavioral performance [3]. Pupillometry data of both human subjects and animal models have been utilized in numerous applied studies [1-6], including those on neurodevelopmental disorders [4,5]. This makes a thorough understanding of the dynamics of pupillometry an essential task.

The activity of the brain is highly fluctuating even at the resting state. This intrinsic brain fluctuation may influence the control system of the pupil to produce spontaneous pupillary fluctuations in the time series waveform that possesses a great complexity. Yet, while there are numerous applied studies involving pupil size fluctuations, there seem to be few that investigate its dynamics and properties in detail. In [1,2] pupillometry dynamics from *healthy human subjects* was investigated by methods of nonlinear time series analysis, which have been found useful in numerous studies on the dynamics of complex biological signals [7]. In [1,2] the

applied analysis included the time-delay-reconstruction method, the method of surrogate data, and calculation of correlation dimension, the largest Lyapunov exponent, recurrence plot, recurrence rates and determinism, which are recurrence plot quantification analysis measures. As a result, the determinism of the healthy human subjects' data was reported in both studies, and, additionally, in [2] its dynamics was claimed to be deterministic chaos.

Spontaneous oscillations of pupil size in mouse models have been taken as a noninvasive biomarker to address such important and challenging problem as the early detection of neurodevelopmental disorders like autism [5]. Full understanding of the underlying pupillometry dynamics and the extent to which their properties are similar across species may provide new valuable information that could not be uncovered by previously applied analysis methods, potentially yielding better results in existing studies. While some attention has been paid to human pupillometry dynamics as above, practically no studies have investigated the pupillometry dynamics of mice, which can be experimentally manipulated in preclinical models. Thus, a detailed investigation of mouse pupillometry dynamical characteristics is needed.

Pupillometry data from wild-type (WT) mice are used as a control for comparison with diseased mouse models [5]. So, in this study, we aimed to confirm whether the WT mouse pupillometry data have dynamical characteristics similar to those of healthy human subjects, whose dynamics were found to be deterministic and even claimed to be chaotic [1,2]. Presence of 'determinism' implies that the dynamical system is determined by a certain rule and its evolution is defined by the current state and past information, making it one of the defining properties of deterministic chaos. However, it is a very challenging task to prove that experimentally measured pupillometric data have chaotic dynamics. So, in this study, besides the determinism criterion, we estimated two more important properties of complex dynamical systems, namely trajectory divergence and predictability, which can provide a clue on the underlying pupillometry dynamics. The presence of trajectory divergence as well as the possibility to obtain short-term predictions, i.e. forecast process state in short-time (but not long-time) evolution, are important properties of a chaotic dynamical system. Thus, the determinism, trajectory divergence, and predictability of collected WT data [5] were

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carefully tested by multiple methods of nonlinear time series analysis.

II. MATERIALS AND METHODS

A. Data

Here, spontaneous pupillary fluctuation data recorded by an infrared camera with 50 Hz sampling frequency from 115 WT mice were used. Awake mice were head-fixed but freely moving on a circular treadmill under dim light conditions (50 lux) to allow pupil fluctuations [5]. Pupil size data were collected over 30-minute periods by an infrared camera aimed at the right eye. Data included a variety of age groups from postnatal day P20 to P369. Animal care and experimental procedures were performed in accordance with protocols approved by the Boston Children's Hospital Institutional Animal Care and Use Committee [5]. Detailed information on the experimental procedure can be found in [5].

Data were preprocessed by a low-pass filter with a passband frequency of 6 Hz before the analysis. An example of the resulting pupillometry time series is shown in Fig. 1.

B. Analysis

Methods of nonlinear time series analysis were applied to the WT mouse pupillometry data to unveil its dynamical properties. Most of the methods of nonlinear time series analysis require complete state-space information of the process dynamics. However, for the experimentally measured data often only a single variable observation is all that is available. The method of time-delay reconstruction [7] allows one to obtain possible dynamics of the process in m -dimensional phase space based on single variable observation, $x(t)$. Therefore, first, the possible dynamics was reconstructed in the phase space by the time-delay embedding technique.

To avoid reliance on a single measure to test pupillometry dynamics properties, multiple tests were applied to the reconstructed trajectory. The Wayland test translation error (WTE) [8], which allows to estimate determinism of the data as well as provides an estimate on the level of the noise present in the data, was calculated. Then, the recurrence plot (RP) method [9], which utilizes neighborhood relations to visualize m -dimensional system dynamics as a 2-dimensional binary image, was applied. Depending on the type of system's dynamics RP has a unique pattern that qualitatively characterizes a dynamical system. As the RP provides only qualitative characteristics of investigated data, the recurrence quantification analysis (RQA) [9] was performed. RQA quantifies underlying structures in RP, and, therefore, allows one to go beyond RP image-based qualitative results. Then the largest Lyapunov exponent (LLE), which provides qualitative and quantitative characteristics of the dynamical system, was calculated. Qualitatively, a positive LLE implies the presence of trajectory divergence and is recognized as a hallmark of chaos. Quantitatively the value of the LLE measures the trajectories divergence rate. As the LLE reflects important properties of a dynamical system, it is one of the methods of nonlinear time series analysis frequently used in applied studies. In this study, the LLEs were calculated by the Rosenstein et al. method [10]. Finally, the deterministic nonlinear prediction method was applied to estimate data's predictability. Presence of the short-term predictability can be recognized as a sign of data determinism [7]. Additionally, the

method of surrogate data [11] was applied to the LLE and prediction results to address the issue of the noise contamination in the experimental data.

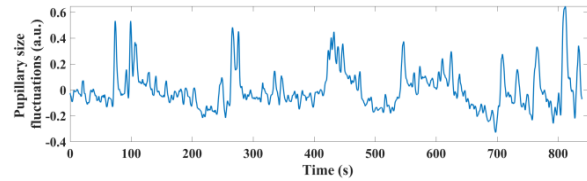


Figure 1. An example of preprocessed wild-type mouse spontaneous pupillary fluctuations time series.

III. RESULTS

A. Time-Delay Reconstruction

The time-delay-reconstructed trajectory was calculated for all datasets. The dimension necessary for the reconstruction was estimated by the false nearest neighbors method [7]. The minimum embedding dimension was estimated as $m=4$ for 22 datasets and as $m=3$ for the rest of the datasets; therefore, the reconstruction dimension was chosen as $m=4$ for further calculations. The value of time delay, τ , applied in time-delay reconstruction was chosen as the time when the time series autocorrelation function falls below $(1-1/e)$. Figure 2 demonstrates an example of the time-delay-reconstructed trajectory corresponding to the time series shown in Fig. 1.

B. Wayland Test Translation Error (WTE)

Figure 3 demonstrates the distribution of WTEs calculated for all datasets. The WTE values close to 0 indicate strong underlying determinism in the data. In contrast, a stochastic process, such as colored noise, produces a WTE value close to 0.5 [12], and an uncorrelated random process, such as white noise, produces a WTE value close to 1. Although there is no clear WTE-value boundary between deterministic and stochastic processes, in previous studies it was discussed [12,13] that WTE values significantly larger than 0, but less than 0.5 can be produced by a deterministic process with a considerable level of noise contamination.

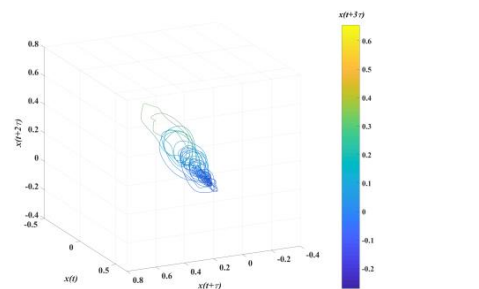


Figure 2. An example of pupillometry time-delay-reconstructed trajectory in the 4-dimensional phase space.

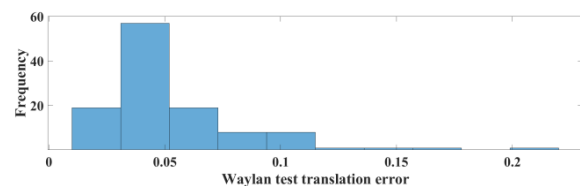


Figure 3. Distribution of the Wayland test translation error values for 115 wild-type mouse pupillometry datasets.

C. Recurrence Plot (RP) and Recurrence Quantification Analysis (RQA)

In this study, the calculated RP size was 10000x10000 points. The threshold, which is a parameter required for RP calculation, was chosen as 5% of the size of the trajectory reconstructed in the phase space. To obtain quantitative measures of the pupillometry dynamical characteristics, RQA [9] was conducted on obtained RPs. In this study, the following RQA measures were calculated: determinism (DET), maximal diagonal line length (L_{max}), average diagonal line length (L), and entropy (ENTR). Obtained results are summarized in Table 1.

TABLE 1. SUMMARY OF THE RECURRENCE QUANTIFICATION ANALYSIS RESULTS

Stats	RQA measure			
	DET	L	L_{max}	ENTR
min	0.736	4.167	28	1.807
max	0.997	59.931	9499	3.801
mean	0.966	23.630	3036.435	2.937
deviation	0.040	11.982	2647.737	0.425

D. Largest Lyapunov Exponent (LLE)

The distribution of calculated for all data LLEs is shown in Fig. 4 (blue bars). As seen in Fig. 4, all the LLEs are positive, however, the presence of noise cannot be overlooked as a factor that can cause overestimation of the LLE value. To address the problem of noise in experimental data the method of surrogate data was applied to verify the results of the LLEs calculation. For each pupillometry time series 100 Fourier transform phase-randomized surrogates [11] were generated, and its LLEs were calculated. Then it was tested whether or not the original time series LLE is within its surrogates' LLEs distribution. Figure 4 demonstrates the distribution of 100 surrogate data LLEs (yellow bars with dashed line border) and the LLE value (red diamond-shaped mark) of the original time series (shown in Fig. 1) to which these surrogates correspond.

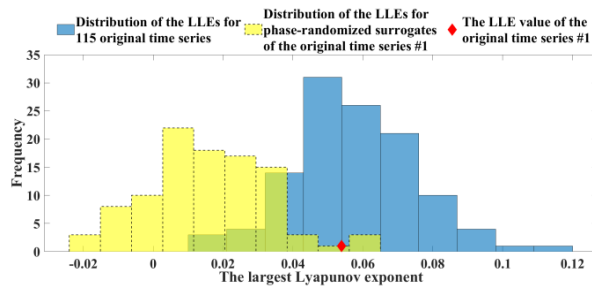


Figure 4. Results of the Lyapunov exponent estimation. Distribution of the largest Lyapunov exponents for 115 wild-type mouse pupillometry datasets (blue bars), the value of the largest Lyapunov exponent of the dataset number 1 (red diamond-shaped mark), and the distribution of the largest Lyapunov exponents calculated for the 100 phase-randomized surrogates corresponding to the dataset number 1 (yellow bars with dashed line outline).

E. Deterministic Nonlinear Prediction

Investigated data predictability was estimated by the deterministic nonlinear prediction method. The correlation coefficient (CC) between original and predicted data for the time series in Fig. 1 is shown in Fig. 5 (red dashed line), where

the prediction step indicates how many data points ahead system state is predicted, and each step corresponds to the physical time equal to the sampling step. The distribution of the CC for the 10 steps prediction for all data is shown in Fig. 6. Similarly to the LLE results, the phase-randomized surrogate data were used to test noise influence on the prediction performance. The CC curves characterizing predictability for 50 surrogate time series are shown in Fig. 5 (black solid lines).

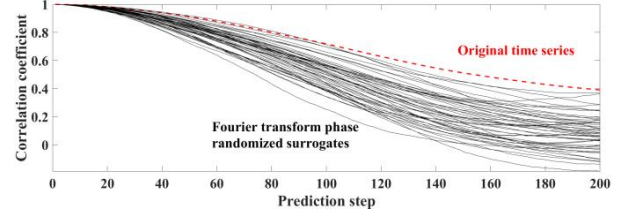


Figure 5. Deterministic nonlinear prediction results. The correlation coefficient between original and predicted data for the original pupillometry time series (red dash-dotted line) and for its 50 surrogates (black solid lines).

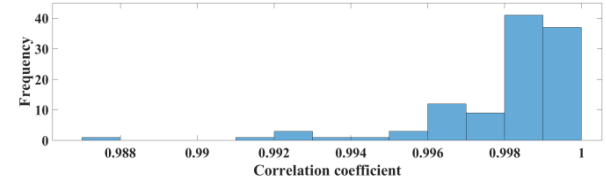


Figure 6. Distribution of the correlation coefficient for 10-steps forward prediction for 115 wild-type mouse pupillometry datasets.

IV. DISCUSSION

The conducted analysis aimed to test different properties of WT mouse spontaneous pupillary fluctuation dynamics [5], in order to clarify whether these properties are similar to those of healthy human subjects reported previously to be deterministic and chaotic [1,2]. First, the minimum embedding dimension – offering an estimate of the number of variables in the dynamical system involved in the creation of pupillometry dynamics – was estimated as 4, which might reflect, for example, the number of major neuromodulatory systems (ACh, NE, DA, 5HT) affecting process dynamics. The 4-dimensional time-delay-reconstructed trajectories calculated for all datasets demonstrated the presence of a certain structure which implies the existence of an attractor. Based on the obtained trajectories, methods of nonlinear time series analysis were applied to the collected data.

One of the primary goals of this study was to demonstrate that similar to human subjects, mouse pupillometry dynamics are deterministic. Pupillometry dynamics are extremely complex, possibly due to interaction with intricate fluctuations produced by the brain. At the same time, experimental data tend to contain a certain amount of noise of unknown nature, which could be almost indistinguishable from the process dynamics. Therefore, rather than relying on a single test, multiple methods are preferable to test the data's dynamical properties. We diagnosed the determinism of pupillometry dynamics using three methods: the Wayland test, RQA's DET calculation, and short-term predictability estimation. The WTE values close to 0 (Fig. 3), DET values close to 1 (Table 1), and presence of short-term predictability (Fig. 5 and 6)

identified strong underlying determinism in the data. However, as seen in Fig. 3 and Table 1, calculated values for several datasets were larger than 0.1 and less than 0.9 for WTE and DET, respectively. This means that a certain amount of noise is likely to be mixed in the data. The presence of observational noise is almost unavoidable for experimental data. At the same time, the biological system itself may produce a system or dynamic noise. Distinguishing types of noise and its levels mixed into the data is highly challenging, but an increase in the WTE value is expected to reflect an overall increase in the noise level [12,13]. Therefore, we can conclude that we are dealing with noise-contaminated deterministic data. Additionally, it is worth mentioning that while the presence of dynamical noise makes dynamics analysis more complicated, once extracted from the signal, dynamical noise may provide important information itself.

As the next step, the LLE was calculated to clarify the trajectories divergence rate. As seen from the distribution in Fig. 4, all LLEs were positive, however, their values were rather small. Positive LLE value is traditionally recognized as an indicator of deterministic chaos; however, data length limitations, imperfection of existing LLE estimation algorithms, as well as presence of noise in the data may lead to misestimation of the LLE. Trajectory divergence is also linked to the RQA's $L_{\max}$ measure, which is the inverse of the divergence. On average, large $L_{\max}$ (Table 1) indicates small divergence in the investigated data, which is consistent with the obtained LLE values. Several datasets demonstrated low $L_{\max}$ values. Taking into account that the same datasets have higher WTE and lower DET values, low $L_{\max}$ values are likely due to the effect of noise in the data, as the noise disturbance of the trajectory leads to misidentification of the neighborhood and the RP diagonal line interruption.

Taking into account the noise contamination issue, to verify the reliability of the obtained LLE results, the method of surrogate data was applied. When there is a clear separation between the results corresponding to the original time series and the surrogate data results, or if the original results lie within less than 5% of the surrogate results distribution, we can assume reliability of the obtained results despite the presence of noise. However, the comparison of the results of the LLE estimation with the distribution of corresponding surrogate data LLEs demonstrated that the original time series LLE was placed close to an inconclusive 5% of surrogate LLEs distribution. This indicates that there might be a significant influence of noise on the data in the LLE calculation results, thus leaving open the question whether the calculated positive LLEs can be treated as an indicator of deterministic chaos in the data.

Another calculated RQA measure is the average diagonal line length, L , which can be interpreted as the mean prediction time. As seen in Table 1, data predictability was recognized as relatively low, which is consistent with the results of the deterministic nonlinear prediction shown in Fig. 5. Additionally, high ENTR values seen in Table 1 indicated the high complexity of the system, as well as its low predictability [9, 14]. Taking into account the results of the surrogate data method application, a fast decrease in prediction quality with time is likely to be caused by the presence of noise in the experimental data.

V. CONCLUSION

This study aimed to investigate properties of WT mouse spontaneous pupillary fluctuation dynamics by the methods of nonlinear time series analysis. Results clearly indicated strong underlying determinism in the data, which, however, was altered in several datasets by a considerable amount of noise. As pupillometry dynamics of human subjects is recognized to be deterministic [1,2], we can assume determinism of spontaneous pupillary fluctuations regardless of species. The presence of determinism is essential for further applied studies on pupillary data.

Additionally, predictability and trajectory divergence rates were also investigated. Although the obtained characteristics were similar to those of time series produced by chaotic dynamics, results of surrogate data method application indicated that the effect of noise in the data cannot be overlooked, and further careful investigation of WT mouse pupillometry data is required.

REFERENCES

- [1] M. L. Rosenberg and M. H. Kroll, "Pupillary hippus: an unrecognized example of biologic chaos," *Journal of biological systems*, vol. 7, no. 1, pp. 85-94, 1999.
- [2] L. Mesin, A. Monaco, and R. Cattaneo, "Investigation of nonlinear pupil dynamics by recurrence quantification analysis," *BioMed Research International*, vol. 2013, pp. 1-11, 2013.
- [3] J. Reimer, M.J. McGinley, Y. Lui, C. Rodenkirch, Q. Wang, D.A. McCormick, and A.S. Tolias, "Pupil fluctuations track rapid changes in adrenergic and cholinergic activity in cortex," *Nature communications*, vol. 7, pp. 13289 1-7, 2016.
- [4] E. Blaser, L. Eglington, A.S. Carter, and Z. Kaldy, "Pupillometry reveals a mechanism for the autism spectrum disorder (ASD) advantage in visual tasks," *Scientific reports*, vol. 4, pp. 4301 1-5, 2014.
- [5] P. Artoni, A. Piffer, V. Vinci, J. LeBlanc, C. A. Nelson, T. K. Hensch, and M. Fagiolini, "Deep learning of spontaneous arousal fluctuations detects early cholinergic defects across neurodevelopmental mouse model and patience," *PNAS*, vol. 117, no. 38, pp. 23298-23303, 2019.
- [6] A. Iriki, M. Tanaka, and Y. Iwamura, "Attention-induced neuronal activity in the monkey somatosensory cortex revealed by pupillometrics," *Neuroscience research*, vol. 25, no. 2, pp. 173-181, 1996.
- [7] M. Shelhamer, *Nonlinear Dynamics in Physiology. A state-Space Approach*. Singapore: World Scientific, 2007.
- [8] R. Wayland, D. Bromley, D. Pickett, and A. Passamante, "Recognizing Determinism in a Time Series," *Physical review letters*, vol. 70, pp. 580-582, 1993.
- [9] N. Marwan, M. C. Romano, M. Thiel, and J. Kurths, "Recurrence plots for analysis of complex systems," *Physics reports*, vol. 438, pp. 237-329, 2007.
- [10] M.T. Rosenstein, J. J. Collins, and C. J. De Luca, "A practical method for calculating largest Lyapunov exponents from small data sets," *Physica D: Nonlinear Phenomena*, vol. 65(1-2), pp. 117-134, 1993.
- [11] J. Theiler, S. Eubank, A. Longtin, B. Galdrikian, and D. Farmer, "Testing for nonlinearity in time series: the method of surrogate data," *Physica D*, vol. 58, pp. 77-94, 1992.
- [12] I. Tokuda, T. Miyano, and K. Aihara, "Surrogate analysis for detecting nonlinear dynamics in normal vowels," *J. Acoust. Soc. Am.*, vol. 110, no. 6, pp. 3207-3217, 2001.
- [13] N. Sviridova and K. Nakamura, "Local noise sensitivity: Insight into the noise effect on chaotic dynamics," *Chaos*, vol. 26, pp. 123102 1-12, 2016.
- [14] G. Leonardi, "A method for computation of entropy in the recurrence quantification analysis of categorical time series," *Physica A*, vol. 512, pp. 824-836, 2018.

査読あり国内会議



アトラクタの2点間距離分布を用いた再構成パラメータ推定

Estimating Reconstruction Parameters Using the Inter-point Distance Distribution on Attractors

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1 はじめに

観測技術の向上により、様々な分野で高精度に時系列データを観測できるようになっている。時系列解析の目標として、時系列データからシステムの理解、良いモデルの生成、正確な予測、効果的な制御などがある。特にシステムの特性を理解することは、最も重要である。非線形時系列解析では、遅延座標系を用いることで、システムの全状態変数を観測できない状況でも、システムの力学的な振る舞いを再構成できることが知られている [1, 2]。しかし、現実世界では、有限長、有限精度のデータしか観測できないことが一般的であり、遅延座標系によって力学系を再構成するためには、再構成次元、遅れ時間を適切に設定する必要がある。

もし適切なパラメータによって力学系のアトラクタを再構成できていれば、再構成アトラクタは元のアトラクタと幾何学的な構造が類似することが期待される。また、アトラクタの2点間距離分布を用いたフラクタル次元推定の手法も提案されている [3]。そこで本稿では、アトラクタの幾何学的な特徴として2点間距離分布に着目し、アトラクタ再構成における最適な再構成次元、遅れ時間の推定方法を検討する。本稿では、アトラクタの2点間距離分布の類似度をJS情報量 [4] を用いて評価する。

2 評価手順および手法

本稿ではカオス力学系の一例として Lorenz 方程式 [5] を用いた。まず、Lorenz アトラクタの x_t, y_t, z_t を $[0, 1]$ の範囲に正規化する。ここで、Lorenz 方程式の第一変数 x_t の正規化は、 $\hat{x}_t = (x_t - x_{\min}) / (x_{\max} - x_{\min})$ で行う。 $\hat{x}_t$ は正規化した x_t , $x_{\max}, x_{\min}$ は x_t の最大値、最小値である。変数 y_t, z_t も同様の方法で正規化し、正規化した Lorenz アトラクタ上の点を $\mathbf{v}(t) = (\hat{x}_t, \hat{y}_t, \hat{z}_t)$ と定義する。次に、正規化した時系列 $\hat{x}_t$ を遅延座標系: $\mathbf{x}(t) = (\hat{x}_t, \hat{x}_{t+\tau}, \dots, \hat{x}_{t+(m-1)\tau})$ に変換する。 m は再構成次元、 τ は遅れ時間である。ここで、正規化 Lorenz アトラクタ上の点 $\mathbf{v}(t)$, 正規化再構成アトラクタ上の点 $\mathbf{x}(t)$ の全てのペア i, j に対して2点間距離 $d(\mathbf{v}(i), \mathbf{v}(j))$, $d(\mathbf{x}(i), \mathbf{x}(j))$ を算出し、平均0, 分散1となるように標準化する。ここで、標準化した2点間距離から2点間距離分布 P_v, P_x を生成する。最後に、2点間距離分布 P_v, P_x 間のJS情報量 $D_{JS}(P_v, P_x)$ を計算する。同様の手順を変数 y, z に対しても行い、 $D_{JS}(P_v, P_y), D_{JS}(P_v, P_z)$ を計算する。

3 数値実験

再構成次元 m と遅れ時間 τ を $1 \leq m \leq 20, 1 \leq \tau \leq 20$ の範囲で変化させた際のJS情報量を求めた。Lorenz

方程式を刻み幅0.01のRunge-Kutta法で解き、過渡状態として100,000点除外し、刻み幅0.1ごとにサンプリングしたデータを1,000点用いた。変数 x に対する結果を図1に示す。

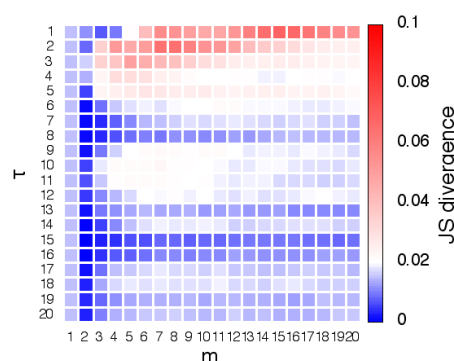


図1 再構成次元 m と遅れ時間 τ を変化させた際のJS情報量(変数 x)

図1より、どの変数においても τ が小さい場合にJS情報量が比較的大きい値となっている。これは、 τ が小さい場合、再構成アトラクタ上の点が重なってしまうためである。一方、埋め込み定理 [2] によれば、アトラクタのフラクタル次元 D_0 に対し、埋め込みとなる m の十分条件は $m > 2D_0$ である。Lorenz アトラクタでは $D_0 \approx 2.06$ [3] であるため、 $m > 2D_0 \approx 4.12$ で埋め込みとなる。しかし、今回はデータ長が1,000と比較的少ないため、 $m = 2, 3$ でJS情報量が最少となったと考えられる。

4 まとめ

本稿では、Lorenz アトラクタとその再構成アトラクタの2点間距離分布間の類似性をJS情報量を用いて評価することで、適切な再構成パラメータが推定可能かを検討した。その結果、比較的短いデータ長では、理論的に埋め込みが保証される再構成次元よりも小さい次元でアトラクタの2点間距離分布が類似することがわかった。本研究の一部は、JSPS 科研費 (No. JP18K18125, JP20H00596, JP21H03514) の援助を受けて行われた。

参考文献

- [1] F. Takens, in *Dynamical Systems and Turbulence, Warwick 1980*, 366–381, Springer, 1981.
- [2] T. Sauer et al., *J. Stat. Phys.*, **65**(3), 579–616, 1991.
- [3] P. Grassberger et al., *Phys. Rev. Lett.*, **50**(5), 346–349, 1983.
- [4] J. Lin, *IEEE Trans. Inf. Theory*, **37**(1), 145–151, 1991.
- [5] E. N. Lorenz, *J. Atmos. Sci.*, **20**(2), 130–141, 1963.



時間制約のない mBSSRP と mBSSRP-S に対する タブーサーチ法を用いた解法の性能比較

Performance evaluation of the tabu search for mBSSRP and mBSSRP-S without time limit constraints

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1 まえがき

バイクシェアリングシステムで生じる自転車の過不足を調整するために, multiple-Vehicle Bike Sharing System Routing Problem (mBSSRP) を提案し, 複数の自転車回収車が短時間で効率的に再配置作業を行うための巡回経路を求めることができる発見的解法の開発を行っている [1]. mBSSRP では回収車に制限時間と容量制約があるため, 一部の問題例に対して実行可能解が得られない場合があった. そこで我々は, 回収車が容量と時間の制約を違反する実行不可解にも遷移が可能な問題 (multiple-Vehicle Bike Sharing System Routing Problem with Soft constraints, mBSSRP-S) を提案した. 数値実験の結果, 時間と容量に関する制約が厳しい問題設定に対しては, mBSSRP-S を解き mBSSRP の実行可能解を得る戦略が短い巡回路を得られた [2]. 本稿では, 制限時間の制約が無い場合にも, mBSSRP-S を解き mBSSRP の実行可能解を得る戦略は有効であるかを調査した.

2 複数の自転車回収車を用いた自転車再配置問題

mBSSRP と mBSSRP-S では, 1 つのデポと自転車が増えたり不足している複数のポートが与えられる. mBSSRP では, 容量制約と時間制約のある複数の回収車が, デポを出発後, 超過しているポートで自転車を回収し, 不足しているポートに自転車を補充, 再びデポに戻るまでの回収車の総移動時間を最小化することが目的である. mBSSRP-S では, 容量と時間に関する制約が取り除かれ, これらの違反量が目的関数に加えられる. 本稿の問題設定では, 制限時間が無い場合 mBSSRP-S の目的関数は, $T(t) + P(t) \times \beta(t)$ である. $T(t)$ は t イタレーション目の回収車の総移動時間を示し, mBSSRP の目的関数である. $P(t)$ は, t イタレーション目に回収・補充できなかった自転車台数を示す. $\beta(t)$ は t イタレーション目の重み係数である. t 回目の探索で容量制約を違反した場合, $t+1$ 回目の探索では, $\beta(t+1) = \lambda\beta(t)$ となり, 違反しなかった場合は, $\beta(t+1) = \mu\beta(t)$ となる [3].

3 mBSSRP と mBSSRP-S に対するタブーサーチ法を用いた解法

mBSSRP と mBSSRP-S の優れた近似解を求めるために, タブーサーチ法を用いて局所探索法を制御する. タブーサーチ法では, 近傍解を生成し, 近傍解の中で最も良い解に遷移する操作を決められた回数繰り返す. さらに, 再び同じ解に遷移することを防ぐために, 過去の探索履歴をタブーリストと呼ばれるリストに追加する. 本稿では, 近傍解を CROSS-exchange と Or-opt を用いて生成する. CROSS-exchange とは, ある巡回路の部分順

列を他の部分順列と交換する操作である. Or-opt とは, ある巡回路の連続する k ポート以下の部分順列を他の巡回路のポートに挿入する操作である. CROSS-exchange または Or-opt が実行されると, 交換された部分順列の始点の組み合わせがタブーリストに追加され, それらを始点とする操作は一定期間禁止される.

4 数値実験・結果

文献 [4] で公開されているポート数が 90 のメキシコシティの実データに対し性能評価を行った. 各ポートの過不足台数は $-17 \sim +17$, 使用可能な回収車台数は 20 台, 各回収車の最大積載容量は 17 台, 試行回数は 50 回, タブーテニユアは 100, 150, 200, 250, タブーサーチ法の繰り返し回数 5,000, Or-opt で挿入可能なポート数 $k = 30$, 重み係数のパラメータ値は $\beta(0) = 1$, $\lambda = 1.07$, $\mu = 0.3$ と設定して数値実験を行った. 表 1 に実験結果を示す. 表 1 は文献 [5] で報告されている分枝カット法を使用したときの下限からの誤差率を示している. 表 1 より, mBSSRP-S を解くことで短い巡回路を得られていることがわかる.

表 1 文献 [5] で示されている下限からの誤差率 [%].

タブー テニユア	mBSSRP			mBSSRP-S		
	平均	最良	最悪	平均	最良	最悪
100	10.76	6.08	15.58	7.82	5.34	15.99
150	9.44	6.34	14.16	6.99	4.37	8.98
200	7.61	5.23	10.72	6.76	4.77	10.17
250	7.23	4.67	10.12	6.31	4.12	8.31

5 まとめ

本稿では, 実データに対して時間制約のない mBSSRP と mBSSRP-S を解いたときの性能比較を行った. 数値実験の結果, 実行不可能解へも遷移が可能な mBSSRP-S は, 制限時間の制約がない場合に対しても有効であることがわかった. なお, 本研究は JSPS 科研費 (No. JP17K00348, JP19K04907, JP20H000596, JP21H03514) の援助を受けて行われた.

参考文献

- [1] H. Tsushima, et al., *Journal of Signal Processing*, **22** (4), pp. 157–160, 2018.
- [2] H. Tsushima et al., “Strategy for exploring feasible and infeasible solution spaces to solve a multiple-vehicle bike sharing system routing problem,” submitted, 2020.
- [3] 渡辺大貴 他, 信学技報, **118** (413), pp. 51–56, 2019.
- [4] M. Dell’Amico, et al., *Omega*, **45**, pp. 7–19, 2014.
- [5] M. Dell’Amico, et al., *Computers & Operations Research*, **71** pp. 149–162, 2016.

査読なし国内学会

時間窓付き配送計画問題の枝候補削減手法

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あらまし 時間窓付き配送計画問題は、現実の配送サービスを数理モデル化した組合せ最適化問題である。時間窓付き配送計画問題を含む多くの組合せ最適化問題は NP 困難であり、最適解を現実的な時間で求めることは難しいことが知られている。そのため、短い時間で良い解を見つける発見的解法の研究が盛んに行われている。発見的解法で解を探索する際に、明らかに性能の悪い解まで考慮をすると計算時間を浪費する。そこで、最適解に含まれることが期待される解の構成要素(枝)をあらかじめ求めておき、探索する枝候補を削減することで、発見的解法の探索性能を維持しつつ計算時間を削減することが期待される。最も研究されている組合せ最適化問題の一つである巡回セールスマン問題では、このような枝候補の削減により短時間で良い解を求められることがすでに示されている。本稿では、時間窓付き配送計画問題に対して枝候補の削減手法を提案し、削減の有無による発見的解法の性能の変化について調査した結果を報告する。数値実験の結果、時間窓付き配送計画問題においても枝候補の削減により解の性能を維持しつつ、計算時間を大幅に削減できることがわかった。

キーワード 組合せ最適化, 時間窓付き配送計画問題, 枝候補

Edge candidate reduction method for Vehicle Routing Problem with Time Windows

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Abstract Vehicle Routing Problem with Time Windows (VRPTW) is one of the combinatorial optimization problems based on a mathematical model of a real delivery service. Many combinatorial optimization problems, including VRPTW, are known to be NP -hard and it is difficult to find the optimal solution in a realistic time. Therefore, researches on heuristic methods for finding a good solution in a short time have been actively conducted. When searching for a solution by the heuristic methods, they wastes computation time if they take into account solutions with obviously poor performance. To avoid solutions with poor performance, one of the possible methods is to reduce the number of edge candidates by looking for edges that are estimated to be included in the optimal solution. In the traveling salesman problem, which is one of the most studied combinatorial optimization problems, it has already been shown that a good solution can be obtained in a shorter time by reducing the number of edge candidates. In this paper, we report the results of edge candidates reduction for VRPTW. Numerical experiments show that the reduction of edge candidates can significantly reduce the computation time while maintaining the performance of the solution.

Key words combinatorial optimization, VRPTW, edge candidates

1. ま え が き

現在研究が活発に行われている組合せ最適化問題の多くは NP 困難であることが知られている。 NP 困難な問題は $P \neq NP$ 予想の元において現代の計算機を用いて最適解を多項式時間で求めることが難しいと考えられており、現実的な時間で最適解を求めることは困難である。そのため、工学的な観点からは最適解を厳密に求める手法と同様に、最適解に近い良い解を短い時間で求める手法も非常に重要である。このような解法は発見的解法と呼ばれ、様々な最適化問題において研究がなされている。最も研究されている組合せ最適化問題の1つである巡回セールスマン問題 (Traveling Salesman Problem, TSP) では、解の構成要素 (以下、枝) の単純な入れ替え操作のみで高性能な解を求めることができる 2-opt 法や Lin-Kernighan heuristic (LK 法) [1] など、様々な発見的解法が現在も研究されている。さらに、タブーサーチを用いた解探索手法 [2]、カオスニューロダイナミクスを用いた手法 [3] [4] [5] [6] など、メタヒューリスティック解法を応用することで効率よく解を求めるアプローチも存在する。

現在提案されている発見的解法の多くは、枝の入れ替え操作を繰り返し行い現在の解をより良い解に更新することで解を求める。しかし、問題の中に存在する多くの枝は高性能な解には明らかに含まれないような悪い枝である。入れ替え操作を行う枝の組を探す際、すべてのパターンを対象とすることは、悪い枝を含む解を計算することを意味する。すなわち、全ての枝を探索することで無駄な計算を繰り返すこととなり、高性能な発見的解法を用いても多くの計算時間を必要とする。そのため、発見的解法を用いる前に最適解を構成すると推測される枝をあらかじめ求めておき、枝の入れ替えを行う候補 (以下、枝候補) を少なくすることが有効である。

TSP の最も簡単な枝候補の削減手法として、座標の近い都市同士との枝のみを枝候補とする手法が用いられている [3] [4] [5] [6]。また、最小全域木を用いた枝候補の削減手法をにより LK 法の計算時間や解性能を改良した Lin-Kernighan-Helsgaun heuristic (LKH 法) [7]、メタヒューリスティック解法の一つである Partial OPTimization Metaheuristic under Special Intensification Conditions (POPMUSIC) [8] を用いた高速な枝候補生成手法 [9] が提案されている。我々も、POPMUSIC を用いた枝候補削減手法を改良し、発見的解法の計算時間をより短縮できる枝候補削減手法を提案している [10] [11]。

NP 困難な組合せ最適化問題の1つに、時間窓付き配送計画問題 (Vehicle Routing Problem with Time Windows 以下、VRPTW) がある。VRPTW は、配送車の積載容量と顧客の宅配受付可能時間の制約を伴った、配送車台数とトラックの総移動距離を最小化する問題である。VRPTW は、現実の宅配サービスを元に考案された問題であり、宅配サービスの需要が増加した近年非常に注目を集めている。VRPTW でも貪欲法を応用した解法 [12]、単純な枝の削除操作と挿入操作を繰り返す解法 [13] など、様々な発見的解法がすでに提案されている。また、遺伝的アルゴリズムを応用した解法 [14] [15]、カオスニューロダイナ

ミクスを用いた手法 [16] などのメタヒューリスティックアルゴリズムを用いた解法も研究されている。さらに問題の定式化についても調査されており、制約条件を緩和することでより効率的に解探索する研究も存在する [17]。

VRPTW では様々な発見的解法が研究されている一方で、発見的解法で探索する枝候補の削減手法については、ほとんど検討がなされていない。そこで本報告では、VRPTW の問題に適用可能な枝候補の削減手法を提案する。その際、枝候補削減手法の性能を調査するために、VRPTW の研究で広く用いられている Solomon のベンチマーク問題集 [12] にあるインスタンスと同じ性質を持つ、よりサイズの大きいインスタンスを作成することで検討を行った。作成したインスタンスを用いて数値実験を行った結果、枝候補を削減しても発見的解法における解の性能に与える影響は小さいことがわかった。また、顧客数の大きい問題を発見的解法で解く際に、枝候補を削減することで計算時間を大幅に削減できることがわかった。

2. 時間窓付き配送計画問題 (VRPTW)

時間窓付き配送計画問題 (Vehicle Routing Problem with Time Window, VRPTW) は、時間制約のある配送計画問題である。VRPTW の目的は、積載量に制限のある配送車を複数台用いて、与えられた顧客全てに荷物を輸送するための最も効率的なルートを見つけることである。

VRPTW は、配送車の集合 V 、頂点の集合 N 、有向グラフ $G = (N, E)$ で定義される。配送車に個体差はなく、全て同じ積載量、移動速度を持つ。頂点集合 N は、 n 人の顧客の集合 C と出発デポと帰還デポの合計 $n+2$ 個の頂点の集合である。 $N = \{0, 1, 2, \dots, n, n+1\}$ のうち、0 は出発デポ、 $n+1$ は帰還デポ、 $1, 2, \dots, n$ は顧客を表す。枝集合 E は、デポと顧客や顧客同士の有向の経路の集合を表している。ただし、帰還デポ $n+1$ が始点の枝や出発デポ 0 が終点の枝は存在しない。それぞれの枝 $(i, j) \in E$ ($i \neq j$) には、移動距離 c_{ij} と移動時間 $t_{ij} = c_{ij} + r_i$ (r_i は顧客 i が荷物を受け取るために必要な時間) の情報が与えられる。

配送車の集合 V に含まれる配送車は積載制限 q を持ち、顧客集合 C の顧客 i は需要 d_i と時間窓 $[a_i, b_i]$ を持つ。顧客 i を訪れる配送車は時刻 b_i までに顧客 i に到着しなければならず、時刻 a_i までに到着した場合は a_i まで待機して顧客に荷物の受け渡しをしなければならない。なお、 $q, a_i, b_i, d_i, c_{ij}, t_{ij}$ は非負数であり、 c_{ij}, t_{ij} は三角不等式を満たす。

VRPTW では、2 種類の決定変数 x_{ijk}, s_{ik} が存在する。枝 $(i, j) \in E$ ($i \neq j$) と、配送車の集合 V に含まれる配送車 k に対して、 x_{ijk} は式 (1) で定義される。

$$x_{ijk} = \begin{cases} 1 & \text{配送車 } k \text{ が頂点 } i \text{ から } j \text{ に直接向かう} \\ 0 & \text{配送車 } k \text{ が頂点 } i \text{ から } j \text{ に直接向かわない} \end{cases} \quad (1)$$

この決定変数 x_{ijk} を用いて、VRPTW の目的関数は式 (2) で定義される。

$$\text{minimize} \quad \sum_{k \in V} \sum_{i \in N} \sum_{j \in N} c_{ij} x_{ijk} \quad (2)$$

決定変数 s_{ik} は、顧客 i が配送車 k から荷物を受け取る時刻を示す。配送車 k が顧客 i に荷物を受け渡さない場合、すなわち $x_{ijk} = 0$ ($j \in N \setminus \{0, i\}$) のとき、 s_{ik} の値は意味を持たない。

VRPTW の目的は、以下の条件を満たす配送車の経路の総移動距離を最小化することである。

- 各顧客 $i \in C$ にちょうど 1 度だけ訪れ、荷物の受け渡しを行う。
- 配送車の積載容量を超えない。
- すべての配送車は出発デポ 0 から出発し、帰還デポ $n+1$ に帰還する。
- 顧客の時間窓の間に荷物の受け渡しを行う。

これらの制約は、式 (3)~(9) で表される。各変数を表 1 に示す。式 (3) は、顧客を 1 度だけ訪問することを表す。式 (4) は配送車とその容量までしか荷物を運べないことを表す。また、式 (5), (6), (7) は、それぞれの配送車が出発デポを出発すること、顧客に到着した後に別の目的地に向けて出発すること、すべての配送車が最後に帰還デポに到着することを表す。式 (8) は、訪れる顧客の順番と受け渡し開始の時刻に矛盾が生じてはいけないことを表す。また、式 (9) は配送車が顧客の時間窓の範囲内に受け渡しをすることを表す。なお、使用しない配送車 k の決定変数は $x_{0,n+1,k} = 1$ とし、空の配送路を走行するものとして定式化される。

$$\sum_{k \in V} \sum_{j \in N} x_{ijk} = 1 \quad \forall i \in N \quad (3)$$

$$\sum_{i \in N} d_i \sum_{j \in N} x_{ijk} \leq q \quad \forall k \in V \quad (4)$$

$$\sum_{j \in N} x_{0jk} = 1 \quad \forall k \in V \quad (5)$$

$$\sum_{i \in N} x_{ihk} - \sum_{j \in N} x_{hjk} = 0 \quad \forall h \in C, \forall k \in V \quad (6)$$

$$\sum_{i \in N} x_{i,n+1,k} = 1 \quad \forall k \in V \quad (7)$$

$$x_{ijk}(s_{ik} + t_{ij} - s_{jk}) \leq 0 \quad \forall i, j \in N, \forall k \in V \quad (8)$$

$$a_i \leq s_{ik} \leq b_i \quad \forall i \in N, \forall k \in V \quad (9)$$

3. VRPTW のインスタンス

VRPTW の研究で一般的に広く用いられている Solomon のベンチマーク問題集 [12] のインスタンスは、計算機を用いて数値的に作成されたものである。インスタンス R101 の顧客とデポの配置を図 1 に示す。インスタンス R101~R112 は以下のように作成されている。

- 顧客は二次元平面上に配置されており、それぞれの顧客 i の座標 (p_{ix}, p_{iy}) は $0 < p_{ix} < 70, 0 < p_{iy} < 80$ の一様整数乱数で与えられる。
- 出発デポと帰還デポの座標 $(p_{0x}, p_{0y}), (p_{n+1x}, p_{n+1y})$ は同じ座標 (35, 35) に存在する。
- 頂点 i, j 間の移動距離 c_{ij} は、2 頂点間のユークリッド距離で与えられる。

表 1 各変数の説明

変数	説明
i, j, k	変数のインデックス
V	配送車の集合
C	顧客の集合
N	顧客とデポの集合
n	顧客の数
c_{ij}	頂点 i, j 間の移動距離
r_i	顧客 i の受け渡しにかかる時間
t_{ij}	頂点 i から j までにかかる時間 ($t_{ij} = c_{ij} + r_i$)
q	配送車の積載制限
d_i	顧客 i の需要量
a_i, b_i	顧客 i の時間窓の始点、終点
x_{ijk}	配送車 k が頂点 i から j に直接向かうか
s_{ik}	顧客 i が配送車 k から荷物を受けとる時刻

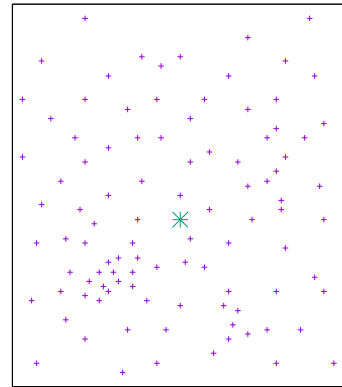


図 1 インスタンス R101 [12] の顧客とデポの配置 (紫点: 顧客, 緑点: デポ)

- 顧客 i の荷物の受け渡しにかかる時間 r_i の値は全て 10 で統一されている。
- 配送車の積載制限は $q = 250$ 。
- 宅配の時間帯は 0 ~ 230 の間で与えられる。
- 各顧客 i の需要量 d_i は $0 < d_i < 45$ の一様乱数で与えられる。
- 顧客の数 n は全て 100。

R101~R112 で異なる点は、時間窓の割り当て方法である。R101~R112 に対する割り当て方法を表 2 に示す。表の顧客のタイプを表 3 に示す。

Solomon のベンチマーク問題の多くは最適解が判明しており様々な論文で用いられている一方で、枝候補の性能を調査するためには顧客数が少なすぎるという問題がある。そこで本稿では、Solomon のベンチマーク問題集のインスタンスと同様の作成手法で顧客数 $n = 200 \sim 1,000$ の新しいインスタンスを、各時間窓の割り当て方法ごとに作成した。

4. 枝候補の削減手法

VRPTW の問題を構成する全ての枝の集合 E には $n^2 + n + 1$ 本の枝が存在する。この中で最適解に含まれる枝の本数は高々

表2 それぞれのインスタンスの特徴

インスタンス	詳細
R101	全ての顧客がタイプ 1
R102	タイプ 1 が 75%, タイプ 4 が 25%
R103	タイプ 1 が 50%, タイプ 4 が 50%
R104	タイプ 1 が 25%, タイプ 4 が 75%
R105	全ての顧客がタイプ 2
R106	タイプ 2 が 75%, タイプ 4 が 25%
R107	タイプ 2 が 50%, タイプ 4 が 50%
R108	タイプ 2 が 25%, タイプ 4 が 75%
R109	全ての顧客がタイプ 3[35:85]
R110	全ての顧客がタイプ 3[20:150]
R111	全ての顧客がタイプ 3[15:195]
R112	全ての顧客がタイプ 3[70:170]

表3 顧客の時間窓のタイプ一覧

タイプ	詳細
1	時間窓の長さが 10 の顧客
2	時間窓の長さが 30 の顧客
3	時間窓の長さが $TW_{\min} \sim TW_{\max}$ の顧客 ($[TW_{\min} : TW_{\max}]$ と表記)
4	いつ届けても良い顧客

$2n$ 本であり、少なくとも $n^2 - n + 2$ 本以上の枝は最適解に含まれない余分な枝である。これら全ての枝を発見的解法で探索すると、多くの計算時間を余分な解の探索に浪費してしまうこととなる。そのため、発見的解法を用いて解を求める前にあらかじめ最適解に含まれると推測される枝を抽出しておくことで、明らかに悪い解への遷移を回避できるため、発見的解法の計算時間を削減することができる。

枝候補に含まれる枝の本数が少ないほど、発見的解法での計算時間は削減することができる。一方で、枝候補に含まれる最適解の枝本数が少ないと、発見的解法で良い解まで無視してしまうことになり、良い解を得られなくなる。すなわち、枝候補には最適解に含まれる枝を残しつつ不要な枝のみを削減することが重要である。このことは、発見的解法だけでなく探索を行う枝候補を削減する手法も重要であることを意味している。

VRPTW において最適解に含まれると推測される良い枝の最も重要な特徴の 1 つは頂点間の距離が短いこと、すなわち c_{ij} が小さいことである。これは、TSP などの他の組合せ最適化問題にも共通している。しかし、配送時間が関与する VRPTW では単なる顧客との距離だけではなく、顧客同士の時間窓の関係性、すなわち時間的距離も重要であることが推測される。そこで、頂点間の物理的な距離に加えて時間的距離を考慮した頂点 i, j 間の距離指標 δ_{ij} を式 (10) のように定義する。

$$\delta_{ij} = \alpha_1 c_{ij} + \alpha_2 (a_j - b_i - t_{ij}) + \alpha_3 (b_j - a_i - t_{ij}) \quad (10)$$

$$\alpha_1 + \alpha_2 + \alpha_3 = 1, \alpha_1 > 0, \alpha_2 > 0, \alpha_3 > 0$$

距離指標 δ_{ij} は、3 つの指標を $\alpha_1, \alpha_2, \alpha_3$ で重み付して計算される。 α_1 で重み付けされている c_{ij} は物理的な距離の重みを表している。 α_2 で重み付けされている $a_j - b_i - t_{ij}$ は、到達

点 j の時間窓の開始時刻から出発点 i の時間窓の終了時刻と移動にかかる時間を引いたものである。これは、頂点 i から j に直接向かった際に頂点 j で待機しなければならない最短の時間である。待機しなければならない時間が短いほど、頂点 i, j 間の距離は近い。また、 α_3 で重み付けされている $b_j - a_i - t_{ij}$ は、到達点 j の時間窓の終了時刻から出発点 i の時間窓の開始時刻と移動にかかる時間を引いたものである。これは、頂点 i から頂点 j に直接向かう際にどれだけ時間の余裕があるかを表している。この値が大きいほど頂点 i から頂点 j に直接行く必要性は薄いため、頂点 i, j 間の距離は遠い。

距離指標 δ_{ij} を用いて、全ての枝集合 E の中から優れていると推測される枝候補 E' を作成する。手順は以下の通りである。

- (1) 枝候補 $E' = \{\phi\}$ とする。
- (2) ある顧客 i からの距離指標 δ_{ij} が小さい順に顧客 j を l 個選び、それぞれとの有向枝 (i, j) を E' に追加する。
- (3) 手順 (2) を全ての顧客 i について行う。
- (4) 出発デポ 0 からの距離指標 δ_{0j} が小さい順に顧客 j を l' 個選び、それぞれとの有向枝 $(0, j)$ を E' に追加する。
- (5) 帰還デポ $n+1$ からの距離指標 $\delta_{j, n+1}$ が小さい順に顧客 j を l' 個選び、それぞれとの有向枝 $(j, n+1)$ を E' に追加する。

5. 数値実験

5.1 距離指標 δ_{ij} の適切なパラメータの調査

Solomon のベンチマーク問題集 [12] の 100 顧客問題に対して枝候補 E' の作成を行い、距離指標 δ_{ij} の適切なパラメータ $\alpha_1, \alpha_2, \alpha_3$ の調査を行った。数値実験の結果を図 2 に示す。ヒートマップの横軸はパラメータ α_1 を、縦軸はパラメータ α_2 を表している。 α_3 は α_1, α_2 が定まれば、 $\alpha_1 + \alpha_2 + \alpha_3 = 1$ より一意に定まる。また、カラーバーは E' に含まれる最適解を構成する枝の本数を表している。最適解に含まれる枝が多いほど、その候補は良い。また、各頂点から枝候補に加える枝の本数 l, l' はそれぞれ $l = 5, l' = 20$ に設定した。

この数値実験の結果から、 $\alpha_1 + \alpha_2$ の値が大きいほど最適解に含まれる枝が多くなることがわかる。また、 α_1 の値が大きいほどより最適解の枝が多くなることもわかる。これらの結果から、 $\alpha_1 = 1, \alpha_2 = \alpha_3 = 0$ のときに最も良い枝候補 E' が得られることが判明した。 α_2, α_3 は時間的距離の重みであることから、枝候補を作成する際に時間要素の考慮は不要である。そこで、以降の数値実験では $\alpha_1 = 1, \alpha_2 = \alpha_3 = 0$ として枝候補の作成を行う。

5.2 適切な枝本数 l, l' の推定

Solomon のベンチマーク問題集を元で作成したサイズの大きいインスタンスを用いて、枝候補 E' を作成する際に用いる顧客からの枝の本数 l とデポからの枝の本数 l' について調査を行った。実験に使用したアルゴリズムは、最近傍構築法 [12] と 3-opt 法 [14] である。最近傍構築法で作成された初期解を、削減した枝候補 E' を用いた 3-opt 法で解の更新を行った。R101 と同じ時間窓の割り振りを行った 500 顧客問題に対して数値実験を行った結果を図 3 に示す。図の横軸は顧客数 n を基準

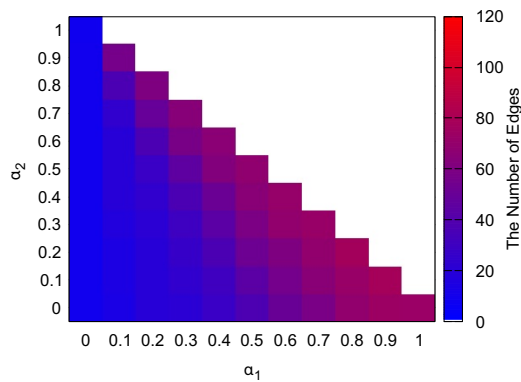


図2 距離指標のパラメータ $\alpha_1, \alpha_2, \alpha_3$ と枝候補の性能の関係性

とした顧客からの枝本数 l の割合 $l/n \times 100(\%)$ を、縦軸はデポからの枝本数 l' の割合 $l'/n \times 100(\%)$ を表している。カラーバーは計算時間と、誤差率を表している。計算時間、誤差率共に小さいほどその枝候補 E' は良い枝候補である。なお、作成した問題は最適解を算出することが困難であるため、上記の方法で作成された解の中で最も目的関数の小さい解を既知最良解とし、その解との誤差率を計算した。

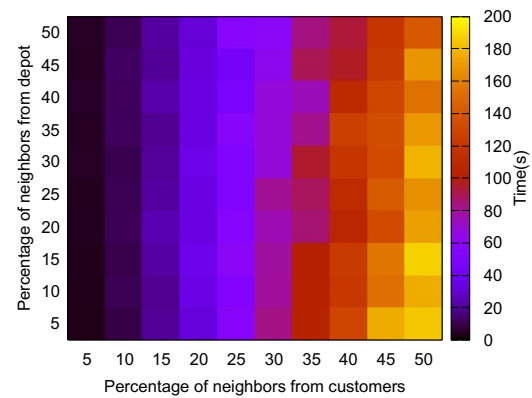
計算時間を見ると、顧客からの枝本数 l が増えるほど計算時間も増加していることがわかる。また、誤差率を確認すると顧客からの枝本数 l の割合が 20% を超えた領域ではほとんど変化していないことがわかる。これらの結果は、顧客からの枝本数を削減することで解の性能を維持しながら計算時間を大幅に削減できることを示すものである。

一方で、デポからの枝本数 l' に着目すると、 l' の値は計算時間にほとんど影響を与えていないことがわかる。一方で、誤差率は顧客からの枝本数 l の割合が 10 ~ 15% 程度である場合、 l' の値が大きいことで誤差率が少し改善されていることがわかる。このことから、デポからの枝は削減する必要はなく、全てのデポとの枝を削減された枝候補 E' に加えるべきであることがわかった。

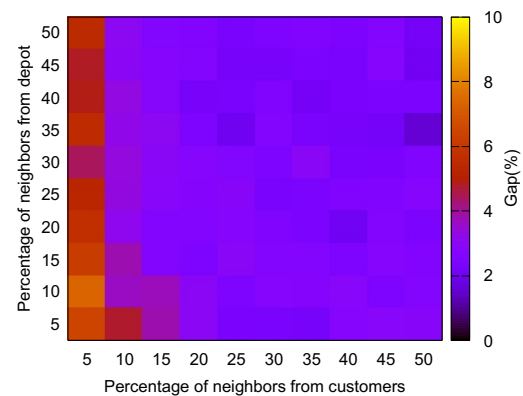
5.3 枝候補削減の有無による発見的解法の性能の変化

Solomon のベンチマーク問題を元に作成したサイズの大きいインスタンスについて、全ての枝集合 E を用いて発見的解法を実行した場合と、削減した枝候補 E' を用いて発見的解法を実行した場合の計算時間と誤差率の比較を行った。使用した発見的解法は、5.2 節の数値実験で用いた方法と同様に、最近傍構築法で作成した解を 3-opt 法で解の更新を行った。枝候補の削減手法で用いた枝の本数 l, l' はそれぞれ $l = 0.2 \times n, l' = n$ である。R101 と同じ時間窓の割り振りで作成した問題を用いた場合の数値計算の結果を図 4 に示す。横軸はインスタンスの顧客数を表しており、縦軸は計算時間、誤差率を表す。また、緑線は枝候補の削減を行わなかった場合を、紫線は枝候補の削減を行った場合を表している。

計算時間の推移に着目すると、枝候補の削減を行わない場合は、顧客数が増えるほど、計算時間が二次関数的に増加して



(a) 計算時間



(b) 誤差率

図3 枝候補 E' の枝本数と発見的解法の関係性

いることがわかる。特に、1,000 顧客問題では 2,500 秒以上かかることが分かる。一方で、枝候補を削減することで 1,000 顧客問題であっても計算時間を 200 秒程度に抑えられていることがわかる。このことから、枝候補を削減することで計算時間を大幅に減らすことができることがわかった。一方、誤差率の推移について着目すると、枝候補を削減した方が誤差率は多少増加してしまうことがわかる。しかし、削減された計算時間と比較すると増加率は少ない。これらのことから、枝候補の削減を行うことで、少ない誤差率の増加で計算時間を大幅に削減できることがわかった。

6. ま と め

本稿では、VRPTW における枝候補の削減手法について提案し、枝候補の性能調査を行った結果について報告した。Solomon のベンチマーク問題集を用いた数値実験を行った結果、時間情報を含めずに枝候補の削減を行うことでより効率的な枝候補の削減が実現できることがわかった。次に、Solomon のベンチマーク問題集を元に作成した顧客数の大きいインスタンスを用いて数値実験を行った。その結果、顧客からの枝は大幅に削減することで枝候補の性能が向上する一方で、デポからの枝の本数は削減するべきではないことが判明した。また、

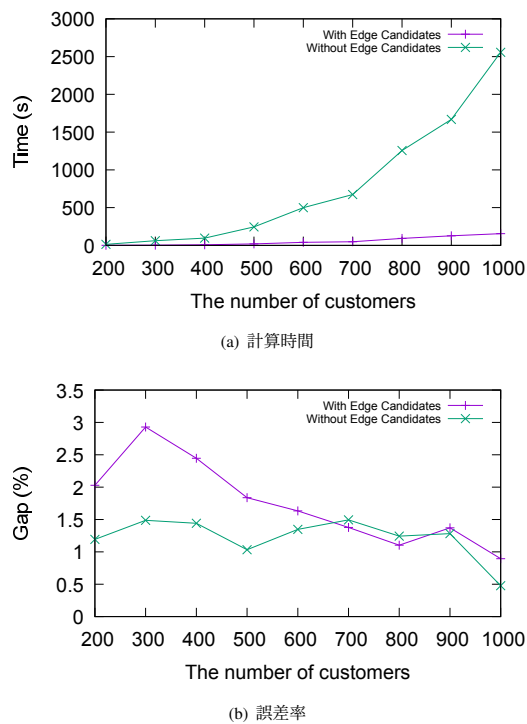


図4 枝候補削減の有無による計算時間と誤差率の比較

枝候補の削減の有無による発見的解法の性能の比較を行った。数値実験の結果、誤差率は変化しなかった一方で、計算時間は大幅に削減されたことがわかった。特に、顧客数の大きい問題において枝候補の削減が計算時間の短縮に貢献していることが明らかになった。

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文 献

- [1] Lin Shen, and Brian W Kernighan, "An effective heuristic algorithm for the traveling-salesman problem," *Operations research*, Vol. 21, No 2, pp. 498–516, 1973.
- [2] Mirosław Malek, Mohan Guruswamy, Mihir Pandya, and Howard Owens "Serial and parallel simulated annealing and tabu search algorithms for the traveling salesman problem," *Annals of Operations Research*, Vol. 21, No. 1, pp. 59–84, 1989.
- [3] Mikio Hasegawa, Tohru Ikeguchi, and Kazuyuki Aihara, "Solving large scale traveling salesman problems by chaotic neurodynamics," *Neural Networks*, Vol. 15, No. 2, pp. 271–283, 2002.
- [4] Takafumi Matsuura and Tohru Ikeguchi, "Chaotic search for traveling salesman problems by using 2-opt and Or-opt algorithms," *Lecture Notes in Computer Science*, Vol. 5164, 2008.
- [5] Shun Motohashi, Takafumi Matsuura, and Tohru Ikeguchi, "Chaotic search method using the Lin-Kernighan algorithm for traveling salesman problems," *Proceedings of International Symposium on Nonlinear Theory and its Applications 2008*, pp. 144–147, 2008.
- [6] Shun Motohashi, Takafumi Matsuura, Tohru Ikeguchi, and Kazuyuki Aihara, "The Lin-Kernighan algorithm driven by chaotic neurodynamics for large scale traveling salesman problems," *Lecture Notes in Computer Science*, Vol. 5769, 2009.
- [7] Keld Helsgaun, "An effective implementation of the Lin-Kernighan traveling salesman heuristic," *European Journal of Operational Research*, Vol. 126, No. 1, pp. 106–130, 2000.
- [8] Éric D. Taillard, and Stefan Voz, "Popmusic – Partial Optimization

Metaheuristic under Special Intensification Conditions," *Operations Research/Computer Science Interfaces Series*, Vol. 15, No. 27, pp. 613–629, 2001.

- [9] Éric D. Taillard, and Keld Helsgaun, "POPMUSIC for the travelling salesman problem" *European Journal of Operational Research*, Vol. 272, No. 2, pp. 420–429, 2019.
- [10] Masayoshi Tosa, Nanfu Miya, Honami Tsushima, and Tohru Ikeguchi, "A Method for Searching Edge Candidates of TSP," *Proceedings of 2021 RISP International Workshop on Nonlinear Circuits, Communications and Signal Processing (NCSP'21)*, 2AM1–1–4, pp. 206–209, 2021.
- [11] 土佐真義, 宮南風, 對馬帆南, 池口徹, TSP の近似解法に与える枝候補作成手法について, 2021 年電子情報通信学会総合大会講演論文集, D–1–11, 2021.
- [12] Marius M Solomon, "Algorithms for the vehicle routing and scheduling problems with time window constraints," *Operations research*, Vol. 35, No. 2, pp. 254–265, 1987.
- [13] Jean F. Cordeau, Gilbert Laporte, and Anne Mercier, "A unified tabu search heuristic for vehicle routing problems with time windows," *Journal of the Operational research society*, Vol. 52, No. 8, pp. 928–936, 2001.
- [14] Alexander Ostertag, Karl F. Doerner, Richard F. Hartl, Éric D. Taillard, and Philippe Waelti, "POPMUSIC for a real-world large-scale vehicle routing problem with time windows," *Journal of the Operational Research Society*, Vol. 60, No. 7, pp. 934–943, 2009.
- [15] Wenqiang Zhang, Diji Yang, Guohui Zhang, and Mitsuo Gen, "Hybrid multiobjective evolutionary algorithm with fast sampling strategy-based global search and route sequence difference-based local search for VRPTW," *Expert Systems with Applications*, Vol. 114, No. 113151, pp. 1–16, 2020.
- [16] 星野聖, 木村貴幸, 池口徹, 時間枠制約付き配送計画問題に対するカオスダイナミクスを用いたメタヒューリスティック解法, 電子情報通信学会論文誌 A, Vol. 90, No. 5, pp. 431–441, 2007.
- [17] 渡辺大貴, 木村貴幸, ソフトな時間枠制約付き配送計画問題に対するカオス探索法を用いた解法, 電子情報通信学会技術研究報告, Vol. 118, No. 413, pp. 51–56, 2019.

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マーク付点過程に対する力学系再構成と実データへの応用

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あらまし 本稿では、マーク付点過程に対する力学系再構成の手法を、人の指先から計測した光電脈波 (PPG) のデータに対して適用した。具体的には、指先から計測した光電脈波の時系列データの極大値もしくは極大・極小値を抽出することでマーク付点過程を生成した。生成したマーク付点過程のイベント間隔時系列とマーク時系列、もしくはイベント間隔時系列、マーク時系列のみからアトラクタを再構成し、計測した PPG の時系列から再構成したアトラクタと比較した。その結果、元の PPG 時系列から再構成したアトラクタの再帰構造はマーク付点過程から再構成したアトラクタに保持されていることが定性的に確認できた。また、再構成アトラクタの 2 点間距離分布間の類似度を JS divergence により評価した。その結果、マーク付点過程から再構成した 6 種類のアトラクタと元の時系列から再構成したアトラクタの 2 点間距離分布間の類似度に特徴的な傾向は存在しなかった。

キーワード 力学系再構成, 埋め込み, 遅延座標系, マーク付点過程, 2 点間距離分布, Jensen-Shannon divergence

Reconstructing dynamical system from marked point processes and its application to real world data

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Abstract In this report, we applied the method of reconstructing dynamical system for the marked point process to the human photoplethysmogram (PPG) measured from a finger. In particular, we generated a marked point process by extracting the maxima or minima of the photoplethysmographic pulse wave time series. Then, we reconstruct an attractor from the time series of inter-event interval and marked value of the generated marked point process, or only from the time series of inter-event interval and marked value, and compared with the attractor reconstructed from measured PPG time series. As a result, it was qualitatively confirmed that the recurrence structure of the attractor reconstructed from the original PPG time series was retained in the attractor reconstructed from the marked point process. However, no clear trends were found in the similarity between the inter-point distance distributions of the six attractors reconstructed from the marked point process and those reconstructed from the original time series evaluated by the JS divergence between the inter-point distance distributions on the attractor reconstructed from the original PPG data and attractors reconstructed from the marked point processes.

Key words Reconstructing dynamical system, embedding, delay-coordinate system, marked point process, inter-point distance distribution, Jensen-Shannon divergence

1. はじめに

我々の身の回りには、様々な点過程データが存在する。例えば、神経細胞から得られるスパイク列や地震データ、経済データなどはその典型である。また、イベント発生時刻に何らかの情報が付与されたマーク付点過程も実世界に偏在する。地震データの場合は、地震発生時刻にマグニチュード、緯度・経度情報が付与され、株式取引データの場合は、取引時間取引量などの情報が付与されている。これまで我々は、非線形力学系の数理モデルから得られた時系列の極大値を抽出することで生成したマーク付点過程を解析する手法を提案している。具体的には、生成したマーク付点過程から再構成したアトラクタが元の非線形力学系の幾何学的特徴であるアトラクタ上の2点間距離分布を概ね保持することを報告した[1]。このような性質は、観測した時系列データの時空間解像度が低い場合でも元の力学系の特徴を一部再構成できることを示唆するものである。このように、時空間解像度が低い時系列データからでも元の力学系の特徴を捉えられる場合、工学応用上有用となる。例えば、近年普及しているウェアラブルデバイスなどで計測される光電脈波(Photoplethysmography, 以下 PPG) のデータなどから健康状態をモニタリングするために、脈波の特徴を明らかにする研究は盛んに行われているが[2],[3]、どの程度の時空間解像度のデータを計測すれば健康状態のモニタリングに十分となるかなどは明らかでない。もし低い時空間解像度での健康状態のモニタリングが可能となれば、データの処理時間の減少などによる実時間処理装置の開発にも繋がるため重要である。

そこで本稿では、PPG の実データに対し、極大値抽出して得たマーク付点過程と実際に計測された PPG の時系列データからそれぞれアトラクタを再構成し、これらのアトラクタ上の2点間距離分布の類似度を Jensen-Shannon (JS) divergence [4] により評価した。マーク付点過程からアトラクタを再構成する際には、マーク付点過程のイベント間隔 (IEI) とマーク値を用いる場合、IEI のみを用いる場合、マークのみを用いる場合の3パターンで再構成した。また、極大値抽出のみではなく、極大値と極小値を抽出した場合についても同様の実験を行なった。

2. 使用データ

本稿では、指先脈波のデータを計測し、解析に使用した。指先脈波のデータは、パルスオキシメータ(東京デバイスズ 汎用心拍センサ IWS920 開発キット「パルス・ラボ」[5])を用いて非侵襲に計測した。その際、「東京理科大学 人を対象とする医学研究の実施及び倫理に関する規定」に従い、実験手順などを被験者に十分説明し、同意を得たのちに計測を行なった。光電脈波の計測原理は、赤色や赤外線などの LED 光を用いて心拍によって色が変化した指先を透過した光の変化を反対側の受光素子により受け取り、脈波の変動を計測する。本稿では、被験者は健康な 22 歳の女性で、約 5 分間計測し、解析した結果を報告する。

3. 手 法

まず、本稿で用いた極大値抽出によるマーク付点過程の生成[6]について述べる。極大値を抽出することでマーク付点過程を生成する模式図を図1に示す。図1に示すように、任意の

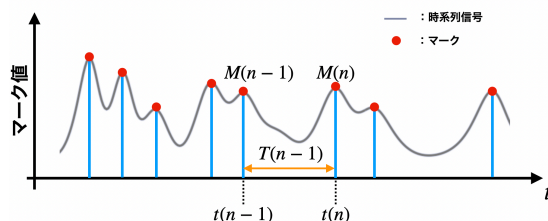


図1 連続時系列の極大値を抽出してマーク付点過程を生成する模式図

時系列信号の n 番目の極大値の時刻をイベント発生時刻 $t(n)$ と定義し、極大値をマーク情報 $M(n)$ と定義することで、マーク付点過程を生成する。このとき n 番目のイベント発生間隔 (IEI) は、 $T(n) = t(n+1) - t(n)$ で定義される。また、極小値を抽出する際も同様の方法でマーク付点過程を生成した。

次に、遅延座標系を用いた力学系の再構成について説明する。観測時系列 $x(t)$ を式(1)のように遅延座標系へ変換することで、仮に力学系の全変数を観測できない場合でも力学系を再構成できることが既に示されている[7],[8]。

$$v(t) = (x(t), x(t+\tau), x(t+2\tau), \dots, x(t+(m-1)\tau)) \quad (1)$$

式(1)において、 m は再構成次元、 τ は時間遅れである。また、多変数が同時計測された時系列データからも力学系の再構成は可能である。我々は既に、マーク付点過程をイベント間隔 (IEI) 時系列とマーク時系列の2次元時系列とみなし、力学系を再構成する方法を提案している[1]。具体的には、式(2)でマーク付点過程から力学系を再構成する。

$$V(t) = (T(t), M(t), \dots, T(t+(m-1)\tau), M(t+(m-1)\tau)) \quad (2)$$

ここで、式(2)において、 τ は遅れ時間で、 $2m$ が再構成次元となる。

本稿では、観測した PPG の時系列データから再構成したアトラクタとその極大値・極小値を抽出して生成したマーク付点過程から再構成したアトラクタの幾何学的特徴が類似しているかを評価する。アトラクタの幾何学的特徴を定量的に評価するためのよく知られた指標としてフラクタル次元がある。また、フラクタル次元を推定するための手法として2点間距離分布を用いる手法も提案されている[9]。我々も既に、アトラクタ上の2点間距離分布の類似度の評価によりアトラクタの類似度を評価する手法を提案している。具体的には、アトラクタ上の2点間距離分布間の JS divergence によりアトラクタの類似度を評価する。

4. 数 値 実 験

本稿では、計測した PPG の時間解像度を 1/10 とした時系列

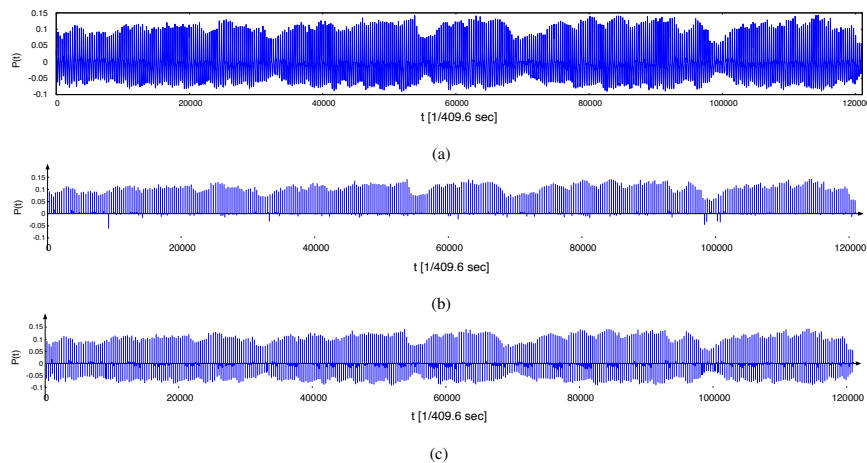


図2 (a) $P(t)$ の時系列波形 (サブサンプル後) と (b) 極大値抽出により得られたマーク付点過程, (c) 極大値と極小値抽出により得られたマーク付点過程

データ $P(t)$ を解析対象とした。計測した時系列データをサブサンプルした理由は、ノイズによる影響を低減するためである。計測の際のサンプリング間隔は $1/409.6$ 秒であるため、 $P(t)$ は $10/409.6$ 秒でサンプリングされている。 $P(t)$ の時系列波形と $P(t)$ の極大値を抽出して生成したマーク付点過程、極大値・極小値を抽出して生成したマーク付点過程を図2に示す。図2から、マーク付点過程はサブサンプルした PPG 波形の大きな変動を捉えていることが確認できる。

次に、 $P(t)$ とその極大値を抽出して生成したマーク付点過程の IEI 時系列とマーク時系列、IEI 時系列のみ、マーク時系列のみから再構成したアトラクタを図3に示す。ここで、 $P(t)$ からアトラクタを再構成する際には $\tau=3$ 、それ以外の場合は $\tau=1$ とした。図3より、 $P(t)$ から再構成したアトラクタはカオスの振舞いを示すことが確認できる。また、図3(b)~(d)を見ると、マーク付点過程への変換による時空間解像度の低下に起因して再構成アトラクタは滑らかな軌道を描かないが、 $P(t)$ が有する再帰構造を保持していることが確認できた。

また、 $P(t)$ の時系列の極大・極小値を抽出して生成したマーク付点過程の IEI 時系列とマーク時系列、IEI 時系列のみ、マーク時系列のみから再構成したアトラクタを図4に示す。ここでも、遅れ時間は $\tau=1$ とした。図4(a)~(c)を見ると、図3(b)~(d)と同様に、 $P(t)$ から再構成したアトラクタの再帰構造を保持していることが確認できた。

最後に、サブサンプルした PPG の時系列から再構成したアトラクタと極大値もしくは極大・極小値を抽出して生成したマーク付点過程から再構成したアトラクタの幾何学的な類似度を提案手法により比較した。再構成次元を2から20の範囲で2刻みで変化させた場合の $P(t)$ から再構成したアトラクタとマーク付点過程から再構成したアトラクタの2点間距離分布間の JS divergence の結果を図5に示す。図5から、JS divergence の値は全ての場合で0.1以下と比較的低い値であることがわかる。一方、再構成次元の変化による JS divergence、すなわちアトラクタの類似度の変化に明らかな傾向は見られない。また、IEI

とマーク時系列を両方使用した場合、IEI 時系列のみを使用した場合、マーク時系列のみを使用した場合、再構成次元の変化により JS divergence の大小関係が入れ替わっている。これらの結果より、マーク付点過程からどのようにアトラクタを再構成しても、元の力学系の特徴を保持していることが示唆される。

5. ま と め

本稿では、指先から計測した光電脈波の時系列に対して、極大値・極小値を抽出してマーク付点過程を生成した。その後、生成したマーク付点過程の IEI とマーク時系列の2次元時系列、IEI 時系列、マーク時系列の1次元時系列のみからアトラクタを再構成した。その結果、定性的には、元の PPG の時系列に内在する再帰構造を保持していることが確認できた。また、マーク付点過程からそれぞれ再構成した6つのアトラクタと計測した PPG の時系列から再構成したアトラクタの2点間距離分布の類似度を JS divergence により評価した。その結果、再構成次元の変化によってそれぞれ6つの再構成アトラクタと元の PPG 時系列の再構成アトラクタの類似度は変動するが高い値を有すること、またどのようにマーク付点過程を構成するかには大きく依存しないことが明らかとなった。今後の課題として、2点間距離分布以外の非線形力学系としての特徴量を比較検討することなどが挙げられる。

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文 献

- [1] K. Sawada, Y. Shimada, and T. Ikeguchi, "Possibility of Reconstructing Nonlinear Dynamical System from Marked Point Process," *Journal of Signal Processing*, Vol.25, No.4, pp.127–131, 2021.
- [2] I. Tsuda, T. Tahara, and H. Iwanaga, "Chaotic pulsation in human capillary vessels and its dependence on the mental and physical conditions," *Proceedings of the Annual Meeting of Biomedical Fuzzy Systems Association: BMFSA 4*, pp.1–40, 1992.
- [3] N. Sviridova and K. Sakai, "Human photoplethysmogram: new insight into chaotic characteristics," *Chaos, Solitons & Fractals*, Vol.77, pp.53–63, 2015.

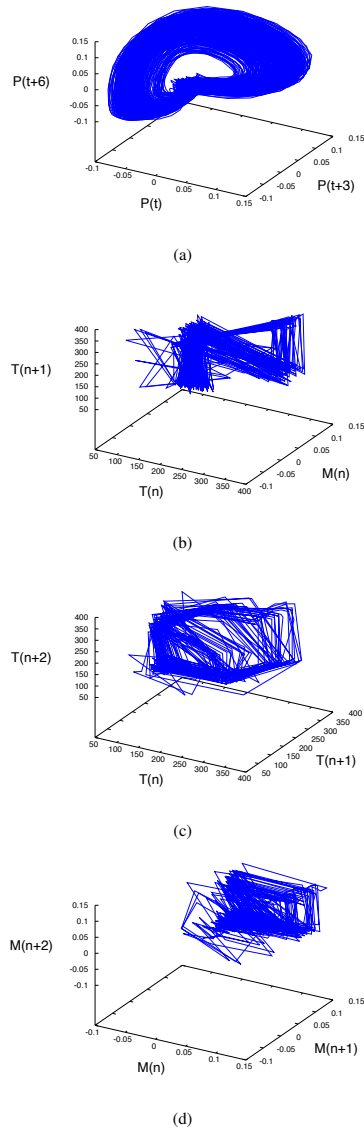


図3 (a) $P(t)$ から再構成したアトラクタ, (b) $P(t)$ から極大値抽出により生成したマーク付点過程の IIEI 時系列とマーク値時系列から再構成したアトラクタ, (c) $P(t)$ から極大値抽出により生成したマーク付点過程の IIEI 時系列から再構成したアトラクタ, (d) $P(t)$ から極大値抽出により生成したマーク付点過程のマーク値時系列から再構成したアトラクタ

- [4] J. Lin, "Divergence measures based on the shannon entropy," *IEEE Transactions on Information Theory*, Vol.37, No.1, pp.145–151, 1991.
- [5] 東京デバイスズ 汎用心拍センサ IWS920 開発キット「パルス・ラボ」
<https://tokyodevices.com/items/188> [accessed 2021/12/21].
- [6] N. Yabuta and T. Ikeguchi, "Prediction of high-dimensional multivariate information as an amplitude-event dynamical system," *Proceedings of NOLTA 2007*, pp.188–191, 2007.
- [7] F. Takens, "Detecting strange attractors in turbulence," *Dynamical Systems and Turbulence*, Vol.898, pp.366–381, 1981.
- [8] T. Sauer, J.A. Yorke, and M. Casdagli, "Embedology," *Journal of Statistical Physics*, Vol.65, No.3, pp.579–616, 1991.
- [9] P. Grassberger and I. Procaccia, "Characterization of strange attractors," *Physical Review Letters*, Vol.50, No.5, pp.346–349, 1983.

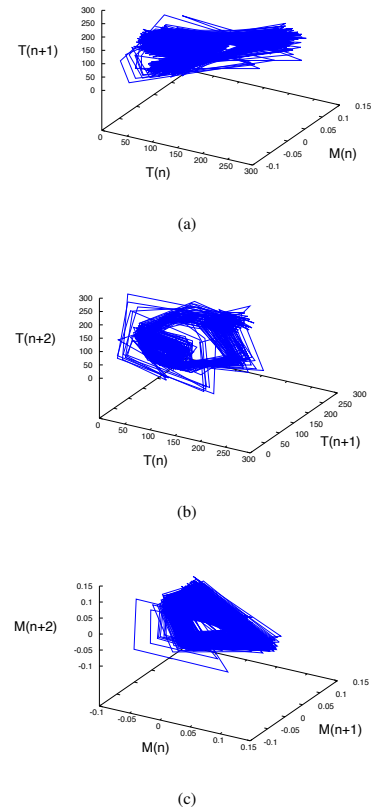


図4 (a) $P(t)$ から極大・極小値抽出により生成したマーク付点過程の IIEI 時系列とマーク値時系列から再構成したアトラクタ, (b) $P(t)$ から極大・極小値抽出により生成したマーク付点過程の IIEI 時系列から再構成したアトラクタ, (c) $P(t)$ から極大・極小値抽出により生成したマーク付点過程のマーク値時系列から再構成したアトラクタ

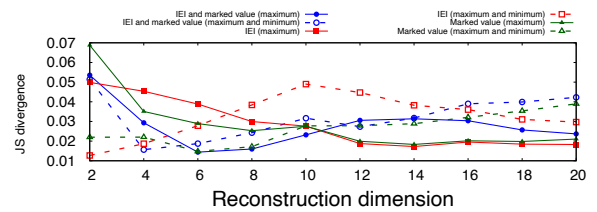


図5 $P(t)$ から再構成したアトラクタとマーク付点過程から再構成したアトラクタの2点間距離分布間の JS divergence. 青色は IIEI とマーク時系列から再構成したアトラクタの結果, 赤色は IIEI 時系列から再構成したアトラクタの結果, 緑色はマーク時系列から再構成したアトラクタの結果である. 実線は極大値のみ抽出して生成したマーク付点過程の結果, 点線は極大・極小値を抽出して生成したマーク付点過程の結果である.

バイクシェアリングシステムの利用履歴の統計的な解析と季節的な影響

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あらまし バイクシェアリングシステムでは、各ポートでの自転車の貸出、返却ができない状況の発生を最小限にするために、自転車回収車がポートを訪問し、自転車の再配置作業を行う必要がある。我々は既に、この再配置作業を短時間で実行する発見的解法の開発に取り組んできた。その際、ポートを決められた範囲内にランダムに配置し、さらに、各ポートにおける自転車の過不足台数もランダムに設定したオリジナルのベンチマーク問題に対して数値実験を行い、提案解法の性能を評価した。しかし、実際のバイクシェアリングシステムにおける再配置作業の効率的な戦略は、実際の履歴情報から得られる現実的なポート配置や利用状況を再配置に組み込むことが重要である。そこで本報告では、ボストン、ワシントン D.C., ニューヨーク、シカゴにおける実際のバイクシェアリングシステムの利用パターンの季節的な変化について、ラスタプロット、変動係数、局所変動係数を用いて解析した結果を報告する。数値実験の結果、季節によって自転車の使用台数は変化するが、貸出と返却される自転車のイベントの発生パターンの統計的特性は1年を通してほぼ変化しないこと、変動係数の値は1より大きく、局所変動係数の値は1に近い値をとることを確認した。

キーワード バイクシェアリングシステム、点過程、変動係数、局所変動係数

Analysis of usage history of bicycle sharing system with seasonal impact

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Abstract In Bicycle Sharing System (BSS), it is necessary for vehicles to visit ports and relocate bicycles to reduce the situation where bicycles cannot be rented or returned at ports. To restore the bicycles in a short time, we developed heuristic methods which can find a near optimal solution in a short time. In the numerical experiments, we have evaluated the performance of the proposed method by producing original benchmark instances with randomly distributed ports and randomly set the number of bicycles. However, an efficient strategy of repositioning operation in a real BSS should be based on realistic port locations and actual usage history data. Therefore, in this study, we report the results of the analysis of the seasonal variation of the actual BSS usage history in Boston, Washington, D.C., New York, and Chicago using raster plots, the coefficient of variation, and the local variation. The results of the numerical experiments show that the value of the coefficient of variation of the pattern of rented and returned bicycles timing was greater than unity and the value of the local variation was close to unity throughout the year for all cities.

Key words bicycle sharing system, point process, coefficient of variation, local variation

1. ま え が き

バイクシェアリングシステムとは、街中に複数のポートと自転車を設置され、利用者は自転車を借りたポートとは異なるポートに自転車を返却することが可能なシステムである¹⁾。バイクシェアリングシステムは、従来の公共交通機関よりも利便性が高い交通システムの1つとしてだけでなく、交通渋滞緩和、排気ガス削減などの観点からも注目されている。例えば、文献[3]では中国の上海の一部の地域を対象に、バイクシェアリングシステムの導入により排気ガスがどれくらい削減可能かが推定されている。数値解析の結果、2016年は8,358トンのガソリンの節約、25,240トンのCO₂の削減、64トンのNO_xの削減が見込めることが報告されている。また、文献[4]では、ワシントンD.C.の公共交通機関の閉鎖がバイクシェアリングシステムの需要に与える影響について調査が行われている。実験の結果、公共交通機関が閉鎖された場合、バイクシェアリングシステムは補助的な交通手段として利用されることが報告されている。2004年において、バイクシェアリングシステムは、世界の13都市でのみ導入がされていたが、IoT技術の発展に伴い2014年には855都市で導入が進んでいる[1]。

バイクシェアリングシステムは、好きな時間に好きなポートで自転車の貸出、返却が可能であるというメリットがある一方、自転車が一方ばかりに利用されてしまうと自転車を借りることができないポート、自転車を返却できないポートが発生する。この問題を解決するため、実際のバイクシェアリングシステムでは自転車回収車を用いて自転車が超過しているポートで自転車を回収し、自転車が不足しているポートに自転車を補充する再配置作業が行われている。この回収車の効率的な巡回経路を求めることは組合せ最適化問題の一種であり、短時間で高性能な解を探索するアルゴリズムの開発に関する研究は盛んに行われている[5],[6]。我々も、複数の自転車回収車の効率的な自転車再配置経路を決定するためにmultiple-Vehicle Bike Sharing System Routing Problem (mBSSRP)を提案し、この問題に対する発見的解法を提案した[7]。しかし、mBSSRPには回収車の容量制約や制限時間制約など厳しい制約条件があるため、一部の問題例に対して実行可能解が得られないという課題があった。そこで我々は、mBSSRPの一部の制約条件を取り除き、それらの違反量を目的関数に加えたmultiple-Vehicle Bike Sharing System Routing Problem with Soft constraints (mBSSRP-S)と、この問題に対する解法を提案した[8]。しかし、mBSSRP-Sでは、mBSSRPの実行可能解のみならず、実行不可能解へも遷移しながら解探索を行うため、ポート数が増加するにつれて計算時間が増加する問題があった。そこで我々はさらに、mBSSRP-Sの解の性能を維持しながら計算時間を削減する方法も提案している[9]。

これらの研究[7]~[9]において我々は、ポートが予め定めら

れた範囲内にランダムに配置されたオリジナルのベンチマーク問題例を用いて、提案手法の性能を評価した。しかし、実際のバイクシェアリングシステムにおける再配置作業の効果的な戦略を開発するためには、実際の履歴情報から得られる現実的なポート配置と利用状況を再配置作業に組み込む必要がある。

一方、近年では、世界中のバイクシェアリングシステムの利用履歴情報や各ポートの利用可能な自転車台数がリアルタイムに公開されており、これらのデータを用いて、実際の利用履歴の解析や自転車の需要予測に関する研究も行われている。例えば、J. Froehlich et al. [12]らは、スペインのパルセロナで行われているBicingのデータ[13] (13週間分の平日のデータを使用)と階層的クラスタリング手法を用いて自転車の利用パターンを解析している。数値実験の結果、370ポートを3つの行動クラスを持つ6つのクラスに分類した。また、A. Kaltenbrunner et al. [14]らも、Bicingのデータ (約400のポートを対象に7週間分の平日と週末のデータ)を使用し、自転車の利用パターンを解析した。その結果、平日と週末では自転車の利用パターンが異なることを明らかにした。さらに、400ポートの中から4つのポートについて、1時間あたりの自転車の利用台数の変化を調査している。その結果、ポートによって自転車の利用パターンは大きく異なることを報告している。一方、G. McKenzie [15]はワシントンD.C. [16]で実施されているスクータシェアとバイクシェアリングシステムの利用パターンの比較を行っている。調査の結果、平日は、2つのピーク (朝夕の通勤の時間帯)、週末は、夕方の5時に利用が増加する傾向があることを報告した。

我々も既に、ボストン [17]、ワシントンD.C. [16]、ニューヨーク [18]、シカゴ [19]の8月の1ヶ月分のデータに対し、自転車の貸出と返却が行われた時間をイベント発生とする点過程として扱い、各ポートの自転車の貸出と返却のイベント発生パターンがどのように振る舞うかを、ラスタプロット、変動係数、局所変動係数を用いて調査した [10], [11]。数値実験の結果、平日と週末、日中 (8:00-20:59)と終日のパターンはほぼ同じであることを確認した。しかし、これまでの利用履歴解析の研究 [10]~[12], [14], [15]では、実際の利用履歴データの一部の期間のみに対する解析に留まっている。

一方、H. Kim [20]は、季節的な変化とPM (particulate matter) レベルが韓国のソウルで実施されているバイクシェアリングシステム [21]の利用に与える影響について調査を行った。実験の結果、PMレベルが高くなる冬と春は自転車の利用時間が短くなる傾向があることを報告している。これは、バイクシェアリングシステムの利用パターンは、一部の期間のみの平日と週末だけでなく、季節によっても変動することを示唆するものである。そこで本報告では、4つの都市 (ボストン、ワシントンD.C., ニューヨーク、シカゴ)についてラスタプロット、変動係数、局所変動係数を用いて自転車の貸出と返却タイミングパターンの統計的特性と季節変化の関係について調査する。数値実験の結果、季節によって自転車の貸出台数は変化するが、貸出、返却タイミングの特徴は、全ての都市について1年を通してほぼ変化しないこと、変動係数の値は1より大きく、局所変動係数の値は1に近い値をとることを確認した。

(注1)：本研究で対象とするバイクシェアリングシステムはポート間で自転車の乗り降りが可能であるシステムであるが、中国では、ポートがなく自由に好きな場所で自転車の乗り降り可能なバイクシェアリングシステムも実施されている[2]。

2. 統計的な解析

本研究では、2019 年のボストン [17], ワシントン D.C. [16], ニューヨーク [18], 2017 年のシカゴ [19] の実際の利用履歴データを使用する。利用履歴データには、自転車が出された日、返却された日、貸出された時間、返却された時間、貸出されたポート ID、返却されたポート ID、利用者の種類が含まれている。

本研究では、自転車の貸出と返却が行われた時間を点過程として扱い、各ポートにおける自転車の貸出と返却のイベントの時間的なパターンがどのように振る舞うか調査を行った。点過程データを解析するために、我々はラスタプロット、変動係数 (C_V)、局所変動係数 (L_V) を使用する。 C_V と L_V を求めるために、inter-event-intervals (IEIs) を求める。1 つのポートにつき貸出と返却の 2 種類の点過程が存在する。まず、 i 番目のポートで自転車の貸出または返却が発生した時間を t_i 、次にそのポートで自転車の貸出または返却が発生した時間を t_{i+1} とする。次に、貸出または返却の i 番目の IEI を $T_i = t_{i+1} - t_i$ と定義すると、IEI を用いて、 C_V , L_V は以下の式で表される。

$$C_V = \frac{\sqrt{\frac{1}{n-1} \sum_{i=1}^n (T_i - \bar{T})^2}}{\bar{T}} \quad (1)$$

$$L_V = \frac{1}{(n-1)} \sum_{i=1}^{n-1} \frac{3(T_i - T_{i+1})^2}{(T_i + T_{i+1})^2} \quad (2)$$

ただし、 n は IEI の数を示し、 $\bar{T} = (1/n) \sum_{i=1}^n T_i$ である。

C_V は全ての IEI の変動を示し、 $C_V = 0$ であれば、自転車の貸出と返却のパターンは規則的に発生している。一方、IEI がポアソン過程の場合、 $C_V = 1$ となる、また、 L_V とは、局所的な変動を測る指標である。 $L_V = 0$ であれば、自転車の貸出と返却のパターンの IEI は規則的に発生し、 $L_V = 1$ であれば、IEI がポアソン過程となる。

3. 数値実験

はじめに、月ごとの自転車の利用回数を図 1 に示す。横軸は月、縦軸は利用回数を示す。図 1 より、全てのバイクシェアリングシステムについて、7, 8, 9 月の自転車の利用は多く、1, 2, 12 月の自転車の利用は少ない傾向にあることがわかる。本研究で対象とした都市は日本と同じように北半球に位置し、四季のある都市である。そのため、気温の高い季節は自転車の利用が多く、気温が低い冬は自転車の利用が少ない傾向になったと考えられる。また、ニューヨークにおけるバイクシェアリングシステムの利用数は他の都市に比べて 3.8 倍 ~ 13.8 倍の利用があることも明らかになった。

次に、各季節の第一水曜日 (平日) と第一土曜日 (週末) の貸出ラスタプロットを図 2 に示す。本研究では、ニューヨークの貸出の結果のみを示しているが、他の都市、また、ニューヨークを含む全都市における自転車が返却されたタイミングのラスタプロットも貸出の結果と同様であった。横軸は時間 (分) を示し、縦軸はポート ID を示している。図 2 より、どの季節も

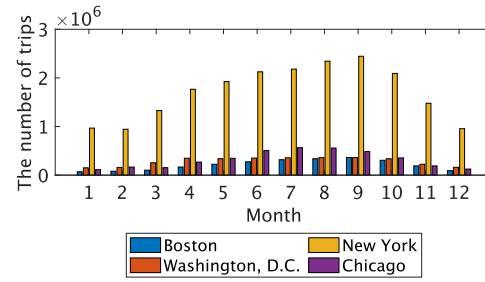


図 1 月ごとの自転車の利用回数。

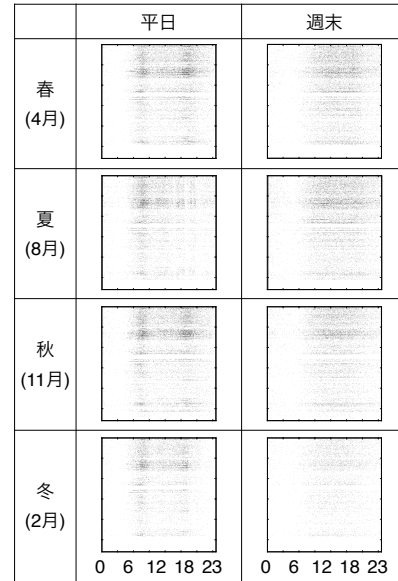


図 2 ニューヨークのバイクシェアリングシステムの貸出された自転車のラスタプロット。

平日は通勤の時間帯に多くの自転車が利用され (午前と夕方にピークを持つ)、休日はピークを持たないパターンがあることがわかる。また、平日、週末ともに夜間の利用はほとんどない。なお、平日の夏 (8 月) のみ夕方のピークが存在しないが、この日は午後から雨が降ったためである。

図 3 は季節ごとの平日と週末の利用履歴を使用し、全てのポートについて C_V を求めた結果である。横軸は C_V 値、縦軸はその頻度を示している。青色の棒は全ての時間帯を使用した場合の C_V である。図 3 では、IEI 数が 1 つ以下のポートは使用していない。図 3 の μ_C は C_V 値の平均を示す。図 3 より、1 日全ての時間帯を利用した場合、全ての都市の全ての季節について C_V 値の平均は 1 よりも大きい値をとっている。図 2 より、深夜の自転車の利用はほとんど存在していない。そこで、21:00 から 7:59 までのイベントを削除して C_V の値を算出した。オレンジ色の棒が、日中 (8:00-20:59) だけのイベントの IEI から求めた C_V の結果を示している。利用されていない時間を削減することにより全ての季節でボストンの C_V 値 (オレンジ色の棒) の平均は 1 に近づいているが、他の都市の C_V 値の平均は 1 より大きい結果となった。

バイクシェアリングシステムにおける自転車の利用は通勤時

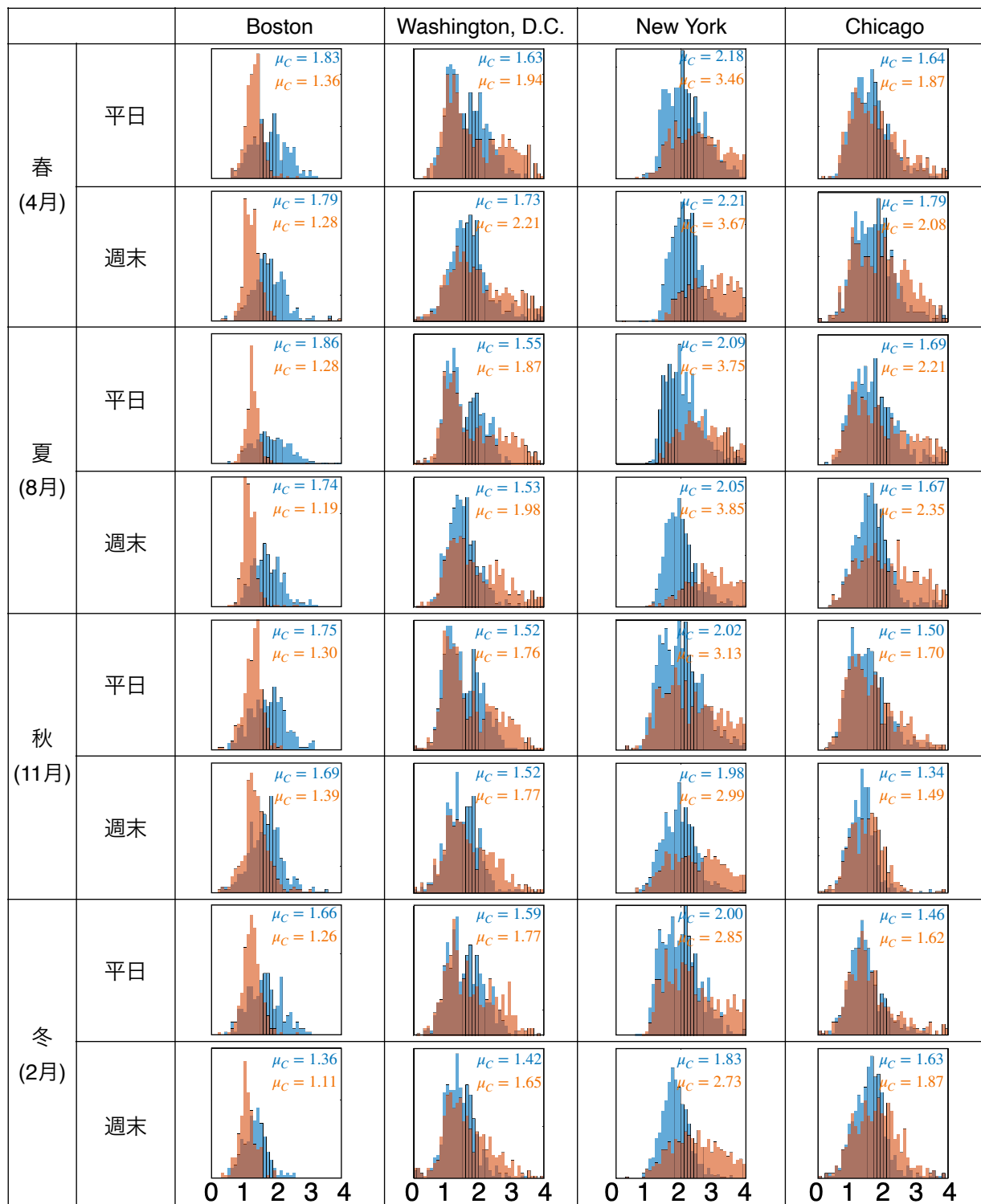
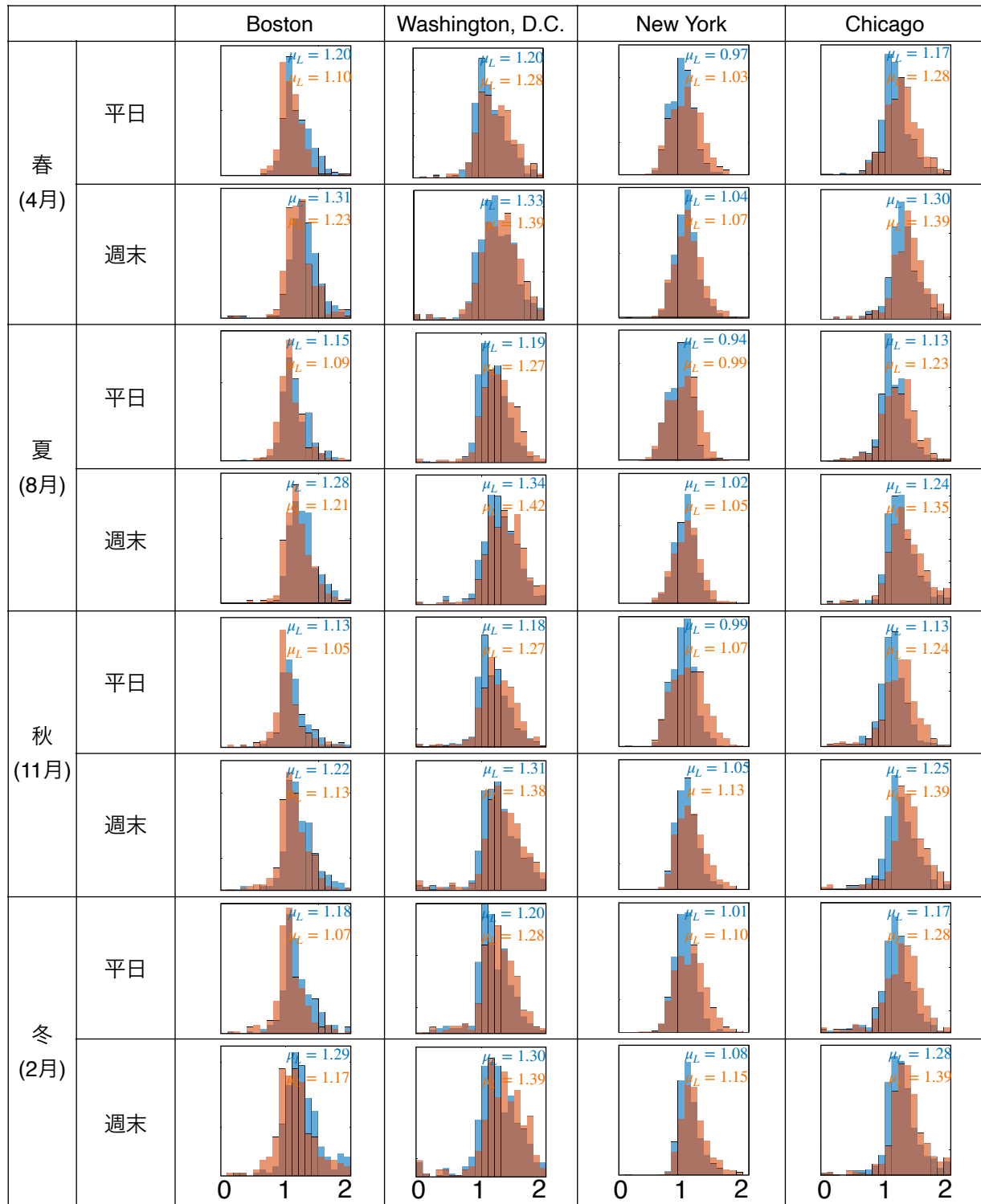


図3 季節ごとの平日と週末の利用履歴を使用し、貸出された自転車の IEI から求めた C_V 値.

図4 季節ごとの平日と週末の利用履歴を使用し、貸出された自転車の IEI から求めた L_V 値.

間帯に多く、深夜はあまり利用されない特性がある。このように、イベント発生間隔の変動が大きい場合、 C_V 値の結果にも影響を与える可能性がある [22], [23]。そこで、イベントの発生する間隔が変動しても IEI の特性を抽出できる局所変動係数 (L_V) を使用する。

図 4 は季節ごとの平日と週末の L_V の結果である。横軸は L_V の値、縦軸は頻度を示しており、青色の棒は、全ての時間 (24h) を使用した場合、オレンジ色の棒は日中 (8:00–20:59) のみを使用した結果である。図 4 の μ_L は L_V 値の平均を示す。図 4 には、貸出のみの結果を示したが、返却された結果も貸出と同様であった。図 4 より、全てのバイクシェアリングシステムについて、平日と週末の日中の L_V (オレンジ色の棒) と 24 時間の L_V (青色の棒) の平均は C_V に比べて 1 に近づいている。また、平日と週末の差は見られない。さらに、それぞれの都市の季節ごとの差も見られない。これらの結果から、4 つの都市における自転車の貸出と返却イベントの発生パターンの統計的特性は、全ての季節について、平日と週末、日中だけを使用した場合 (8:00–20:59) と全ての時間を使用した場合 (24h) で同じ傾向であること、変動係数の値は 1 より大きく、局所変動係数の値は 1 に近い値をとることを確認した。

4. ま と め

本稿では、アメリカのボストン、ワシントン D.C., ニューヨーク、シカゴの実際のバイクシェアリングシステムの利用履歴の季節的な変化についてラスタプロット、変動係数、局所変動係数を用いて解析した結果を報告した。ラスタプロットの結果からは、平日は通勤の時間帯に多くの自転車が利用され、休日はピークを持たないパターンがあることがわかった。平日、週末ともに夜間の利用はほとんどなく、季節間での差は見られなかった。次に、変動係数の結果から、1 日全ての時間帯を利用した場合、全てのバイクシェアリングシステムの全ての季節について変動係数の値の平均値は 1 よりも大きい値をとること、日中 (8:00–20:59) のみの時間を使用した場合は、季節間の差はなかったが、ボストンの変動係数の平均値は 1 に近づくこと、他の都市の場合、変動係数の値の平均値は 1 より大きいことが分かった。最後に局所変動係数を求めた結果からも、季節間の差は見られなく、平日と週末の日中 (8:00–20:59) のみを用いた場合と全ての時間を用いた場合 (24h) の局所変動係数の平均値はともに 1 に近づいており、平日と週末の差も見られなかった。したがって、季節によって使用される自転車台数は変化するが、貸出と返却される自転車のイベントの発生パターンの統計的特性は、1 年を通してほぼ変化せず、平日と週末、日中だけを使用した場合 (8:00–20:59) と全ての時間を使用した場合 (24h) で同じ傾向であり、変動係数の値は 1 より大きく、局所変動係数の値は 1 に近い値をとることを確認した。

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文 献

- [1] Elliot Fishman, “Bikeshare: A review of recent literature,” *Transport Reviews*, vol. 36, no. 1, pp. 92–113, 2016.

- [2] Aritra Pal and Yu Zhang, “Free-floating bike sharing: Solving real-life large-scale static rebalancing problems,” *Transportation Research Part C: Emerging Technologies*, vol. 80, pp. 92–116, 2017.
- [3] Yongping Zhang and Zhifu Mi, “Environmental benefits of bike sharing: A big data-based analysis,” *Applied Energy*, vol. 220, pp. 296–301, 2018.
- [4] Lu Cheng, Zhifu Mi, D’ Maris Coffman, Jing Meng, Dining Liu and Dongfeng Chang, “The Role of Bike Sharing in Promoting Transport Resilience,” *Networks and Spatial Economics*, pp. 1–19, 2021.
- [5] Satomi Wada, Takafumi Matsuura, and Kazumiti Numata, “Heuristic Methods for the Bike-Sharing System Routing Problem,” *Journal of Signal Processing*, vol. 17, no. 4, pp. 115–118, 2013.
- [6] Mauro Dell’Amico, Eleni Hadjicostantinou, Manuel Iori and Stefano Novellani, “The bike sharing rebalancing problem: Mathematical formulations and benchmark instances,” *Omega*, vol. 45, pp. 7–19, 2014.
- [7] Honami Tsushima, Takafumi Matsuura and Kenya Jin’no, “Local Search Method for Multiple-Vehicle Bike Sharing System Routing Problem,” *Journal of Signal Processing*, vol. 22, no. 4, pp. 157–160, 2018.
- [8] Honami Tsushima, Tafumi Matsuura and Tohru Ikeguchi, “Strategy for Exploring Feasible and Infeasible Solution Spaces to Solve a Multiple-Vehicle Bike Sharing System Routing Problem,” *Applied Sciences*, vol. 11, no. 16, 7749, 2021.
- [9] Honami Tsushima and Tohru Ikeguchi, “A searching strategy with low computational costs for multiple-vehicle bike sharing system routing problem,” submitted, 2021.
- [10] Honami Tsushima and Tohru Ikeguchi, “Statistical analysis on usage history of bicycle sharing systems,” *The 2021 Nonlinear Science Workshop*, 発表予定, 2021.
- [11] Honami Tsushima and Tohru Ikeguchi, “Statistical analysis of usage history of bicycle sharing systems,” submitted, 2021.
- [12] Jon Froehlich, Joachim Neumann and Nuria Oliver, “Sensing and Predicting the Pulse of the City through Shared Bicycling,” *Twenty-First International Joint Conference on Artificial Intelligence*, 2009.
- [13] Bicing. <https://www.bicing.barcelona/es>. (最終閲覧日: 2021 年 11 月 15 日)
- [14] Andreas Kaltenbrunner, Rodrigo Meza, Jens Grivolla, Joan Codina, and Rafael Banchs, “Urban cycles and mobility patterns: Exploring and predicting trends in a bicycle-based public transport system,” *Pervasive and Mobile Computing*, vol. 6, no. 4, pp. 455–466, 2010.
- [15] Grant McKenzie, “Spatiotemporal comparative analysis of scooter-share and bike-share usage patterns in Washington, D.C.,” *Journal of Transport Geography*, vol. 78, pp. 19–28, 2019.
- [16] Capital Bikeshare system data. <https://www.capitalbikeshare.com/system-data>. (最終閲覧日: 2021 年 11 月 15 日)
- [17] Bluebikes system data. <https://www.bluebikes.com/system-data>. (最終閲覧日: 2021 年 11 月 15 日)
- [18] Citi Bike system data. <https://ride.citibikenyc.com/system-data>. (最終閲覧日: 2021 年 11 月 15 日)
- [19] Divvy system data. <https://www.divvybikes.com/system-data>. (最終閲覧日: 2021 年 11 月 15 日)
- [20] Hyungkyoo Kim, “Seasonal Impacts of Particulate Matter Levels on Bike Sharing in Seoul, South Korea,” *International Journal of Environmental Research and Public Health* vol. 17, no. 11, 3999, 2020.
- [21] Ddareungi. <https://www.bikeseoul.com> (最終閲覧日: 2021 年 11 月 15 日)
- [22] Shigeru Shinomoto, Keisetsu Shima and Jun Tanji, “Differences in spiking patterns among cortical neurons,” *Neural Computation*, vol. 15, no. 12, pp. 2823–2842, 2003.
- [23] Shigeru Shinomoto, Keiji Miura and Shinsuke Koyama, “A measure of local variation of inter-spike intervals,” *Biosystems*, vol. 79, nos. 1–3, pp. 67–72, 2005.
- [24] Kantaro Fujiwara, Hideyuki Suzuki, Tohru Ikeguchi and Kazuyuki Aihara, “Method for analyzing time-varying statistics on point process data with multiple trials,” *Nonlinear Theory and Its Applications, IEICE*, vol. 6, no. 1, pp. 38–46, 2015.

状態空間再構成の適切なパラメータ推定の検討

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あらまし 本稿では、遅延座標系を用いた力学系再構成の際の適切なパラメータ選択について検討している。具体的には、再構成次元と時間遅れを網羅的に変化させ、真のアトラクタと再構成アトラクタ上の2点間距離分布間の距離を Jensen-Shannon (JS) divergence を用いて計算した。その結果、再構成次元と時間遅れの積を小さい任意定数値に保つことで、JS divergence が最小化することがわかった。加えて、再構成アトラクタ上の2点間距離分布のエントロピーを計算した。その結果、JS divergence を最小化する再構成次元と時間遅れの組み合わせとエントロピーを最大化する再構成次元と時間遅れの組み合わせが概ね対応することがわかった。

キーワード 力学系再構成, 埋め込み, 遅延座標系, 2点間距離分布, Jensen-Shannon divergence, エントロピー

A study on estimating appropriate parameters of state space reconstruction

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Abstract In this report, we investigated appropriate parameter values for reconstructing a dynamical system using delay-coordinate systems. In particular, we calculated the distances between the inter-point distance distributions of the actual and reconstructed attractors through the Jensen-Shannon (JS) divergence by varying the reconstruction dimension and time-delay exhaustively. As a result, we found that the JS divergence is minimized when the product of the reconstruction dimension and the time-delay keeps a small constant value. In addition, we calculated the entropy of the inter-point distance distribution on the reconstructed attractor. As a result, we found that the combinations of reconstruction dimension and time-delay that minimize JS divergence roughly correspond to the combinations of reconstruction dimension and time-delay that maximize entropy.

Key words Reconstructing dynamical system, embedding, delay-coordinate system, inter-point distance distribution, Jensen-Shannon divergence, entropy

1. はじめに

時系列解析では、観測時系列からシステムの特性を理解すること、適切なモデルを構築すること、時系列を高精度に予測すること、システムを効果的に制御することなどが求められる。特に、システムの特性を詳細に理解することは、適切なモデル

の構築、高精度な予測、システムの効果的な制御の成否を決める上で最も重要である。

非線形時系列解析においては、力学系の全ての状態変数を観測できない場合でも、観測時系列に対し、時間遅延座標系を用いることで力学系のアトラクタを再構成できることが広く知られており、再構成の変換が埋め込みとなることは理論的にも示

されている [1], [2]. このように、遅延座標系による力学系の再構成は非線形時系列解析の基盤技術となっている。

遅延座標系への変換による力学系再構成は、再構成の際の遅れ時間値が力学系からの観測時系列の周期倍でないかつ再構成次元が真の力学系のボックスカウント次元の 2 倍以上であれば埋め込みが保証される [2]. この埋め込み定理は、十分な長さのデータが観測されているなど理想的な条件下でのみ保証されるが、現実世界の観測時系列は比較的短い時間のみ観測される場合もある。したがって、実際の解析の場面では、適切な再構成パラメータを選択し、可能な限り良い状態空間を再構成することが肝要である。

適切なパラメータを用いてアトラクタを再構成すると、再構成アトラクタの幾何学的特徴は未知の力学系の背後にある実際のアトラクタと類似することが期待される。アトラクタの幾何学的特徴は、フラクタル次元の一つである相関次元により定量化される。また、アトラクタ上の 2 点間距離分布を用いて相関次元を推定することができる [3]. そこで本稿ではまず、幾何学的特徴としてアトラクタ上の 2 点間距離分布に着目し、Jensen-Shannon (JS) divergence [4] を用いて、真のアトラクタと再構成アトラクタ上の 2 点間距離分布の類似性を最大化する再構成パラメータ値を検討した。その結果、再構成次元と時間遅延の積が小さい定数値であれば、実際のアトラクタと再構成アトラクタ上の 2 点間距離分布は類似することがわかった。埋め込み窓と呼ばれる再構成次元と時間遅延の積を一定に保つことが重要であることは以前から議論されており [5]~[15]、本報告で得たこの結果は、これらの結果と対応している。実際、埋め込み窓を固定することで、相関次元推定の性能が向上することも報告されている [9].

また、実際の時系列解析の場面では、真のアトラクタの情報は未知であるため、再構成アトラクタの情報のみを用いて適切な再構成パラメータを選択する必要がある。そこで、再構成パラメータを変化させた際の再構成アトラクタ上の 2 点間距離分布のエントロピーを計算し、真のアトラクタと再構成アトラクタの 2 点間距離分布間の JS divergence の値が最小になる再構成パラメータの範囲でエントロピーがどのような値を取るか調査した。その結果、真のアトラクタと再構成アトラクタの 2 点間距離分布間の JS divergence の値を最小化する再構成パラメータの範囲は再構成アトラクタ上の 2 点間距離分布のエントロピーを最大化する範囲と概ね対応することがわかった。

2. 手 法

観測時系列に対して、時間遅延座標系を用いた力学系再構成手法は非線形時系列解析において最も広く用いられている。具体的には、観測時系列を X_t ($1 \leq t \leq n$) とすると、式 (1) のように時間遅延ベクトルを構成することで、力学系を再構成する。

$$\mathbf{V}(t) = \{X_t, X_{t+\tau}, \dots, X_{t+(m-1)\tau}\} \quad (1)$$

ここで、 m は再構成次元、 τ は時間遅れ値である。十分長い時系列が観測され、真の力学系の次元に対して十分大きな次元 m で再構成する場合には、式 (1) のような遅延座標系への変換は、

埋め込みとなるものが Takens によって理論的に保証されている [1]. 一方、現実的な時系列解析の場面では、観測時系列の長さには制限がある場合がほとんどであり、状態空間内のデータ点数は $n - (m-1)\tau$ であるため、特に有限長のデータに対しては、可能な限り小さい m と τ で適切な状態空間を構成することが重要である。また、観測時系列のサンプリングレートに対して極端に小さい τ を選択すると、状態空間内のデータ点は不適切に相関が高くなり、極端に大きい τ を選択すると、状態空間内のデータ点は相関がなくなり、不適切な座標系となってしまう。このように、再構成パラメータ m と τ の設定を誤ると、力学系の特徴が再現できないため、遅延座標系による状態空間再構成を行う際には、これらのパラメータを慎重に設定する必要がある。

そこで本稿では、真のアトラクタと再構成アトラクタの 2 点間距離分布の類似性を評価する手法を提案し、アトラクタの空間的な特徴が類似する m と τ にどのような傾向があるか調査した。本稿では、手法の評価に 3 次元の非線形力学系である Lorenz 方程式 [16] を用いた。提案手法では、まず Lorenz 方程式の状態変数 x_t, y_t, z_t を $[0, 1]$ の範囲に正規化する。例えば変数 x_t の場合は、 $\hat{x}_t = (x_t - x_{\min}) / (x_{\max} - x_{\min})$ である。ここで、 $\hat{x}_t$ は正規化した x_t で、 $x_{\max}, x_{\min}$ はそれぞれ x_t の最大値・最小値である。変数 y_t と z_t の場合も同様に正規化し、時刻 t での正規化したアトラクタ上のベクトルを $\mathbf{v}(t) = \{\hat{x}_t, \hat{y}_t, \hat{z}_t\}$ として定義する。加えて、正規化した時系列 $\hat{x}_t$ を正規化した遅延ベクトル $\mathbf{x}(t) = \{\hat{x}_t, \hat{x}_{t+\tau}, \dots, \hat{x}_{t+(m-1)\tau}\}$ に変換する。次に、真のアトラクタ上の点 $\mathbf{v}(i)$ と $\mathbf{v}(j)$ 間の距離を $d_{\mathbf{v}}(i, j)$ 、変数 x の再構成アトラクタ上の点 $\mathbf{x}(i)$ と $\mathbf{x}(j)$ 間の距離を $d_{\mathbf{x}}(i, j)$ と定義する。また、 $d_{\mathbf{v}}(i, j)$ と $d_{\mathbf{x}}(i, j)$ をそれぞれ、平均が 0、分散が 1 となるように、式 (2), (3) で正規化する。

$$\hat{d}_{\mathbf{v}}(i, j) = \frac{d_{\mathbf{v}}(i, j) - \bar{d}_{\mathbf{v}}}{d'_{\mathbf{v}}} \quad (2)$$

$$\hat{d}_{\mathbf{x}}(i, j) = \frac{d_{\mathbf{x}}(i, j) - \bar{d}_{\mathbf{x}}}{d'_{\mathbf{x}}} \quad (3)$$

ここで、 $\bar{d}_{\mathbf{v}}$ と $\bar{d}_{\mathbf{x}}$ はそれぞれ、 $d_{\mathbf{v}}(i, j)$ と $d_{\mathbf{x}}(i, j)$ の平均であり、 $d'_{\mathbf{v}}$ と $d'_{\mathbf{x}}$ はそれぞれ $d_{\mathbf{v}}(i, j)$ と $d_{\mathbf{x}}(i, j)$ の標準偏差である。

次に、正規化した 2 点間距離 $\hat{d}_{\mathbf{v}}(i, j)$ と $\hat{d}_{\mathbf{x}}(i, j)$ から階級数のインデックスを k として 2 点間距離分布 $P_{\mathbf{v}}(k)$ と $P_{\mathbf{x}}(k)$ を生成する。また、階級幅 B は全階級数を N として、式 (4) で決定する。

$$B = \frac{1}{N} \left(\max_{i,j} (\hat{d}_{\mathbf{v}}(i, j), \hat{d}_{\mathbf{x}}(i, j)) - \min_{i,j} (\hat{d}_{\mathbf{v}}(i, j), \hat{d}_{\mathbf{x}}(i, j)) \right) \quad (4)$$

ここで、 $\max_{i,j} (\hat{d}_{\mathbf{v}}(i, j), \hat{d}_{\mathbf{x}}(i, j))$ と $\min_{i,j} (\hat{d}_{\mathbf{v}}(i, j), \hat{d}_{\mathbf{x}}(i, j))$ はそれぞれ正規化した 2 点間距離の最大値・最小値である。最後に、2 点間距離分布 $P_{\mathbf{v}}$ と $P_{\mathbf{x}}$ の間の JS divergence [4] を式 (5) によって求める。

$$D_{\text{JS}}(P_{\mathbf{v}}, P_{\mathbf{x}}) = \frac{1}{2} (D_{\text{KL}}(P_{\mathbf{v}} \| Q) + D_{\text{KL}}(P_{\mathbf{x}} \| Q)) \quad (5)$$

ここで、 D_{KL} は Kullback-Leibler (KL) divergence であり、確率

分布 P_j ($j \in \{v, x, y, z\}$) と Q の間の KL divergence は、式 (6) で定義される。

$$D_{KL}(P_j||Q) = \sum_{k=1}^N P_j(k) \log \frac{P_j(k)}{Q(k)} \quad (6)$$

ただし、確率分布 $Q(k)$ は P_v と P_x の平均の分布 $Q(k) = (P_v(k) + P_x(k))/2$ である。また、本稿では、 $N = 20$ と設定し、変数 y, z についても同様の手順で真のアトラクタと再構成アトラクタ上の 2 点間距離分布間の JS divergence $D_{JS}(P_v, P_y)$ と $D_{JS}(P_v, P_z)$ の計算を行った。

3. 数値実験

3.1 実験条件

本稿では、典型的なカオス力学系として式 (7) の Lorenz 方程式 [16] を用いた。

$$\begin{cases} \dot{x} = \sigma(-x + y) \\ \dot{y} = -xz + rx - y \\ \dot{z} = xy - wz \end{cases} \quad (7)$$

式 (7) において、パラメータは、 $r = 28$, $\sigma = 10$, $w = 8/3$ とした。解は 4 次の Runge-Kutta 法を用いて計算し、その際の刻み幅を 0.01 とした。また、過渡状態として 100,000 データを除外し、状態空間を構成するデータ点数が全ての場合で 5,000 となるようにした。力学系を再構成する際の再構成次元 m と時間遅れ τ は $1 \leq m \leq 20$, $1 \leq \tau \leq 20$ の範囲で変化させた。

3.2 結果

再構成次元と時間遅れを変化させた際の真のアトラクタと再構成アトラクタ上の 2 点間距離分布間の JS divergence の結果を図 1(a), (d), (g) に示す。図 1(a), (d), (g) において、横軸は再構成次元 m 、縦軸は時間遅れ τ 、カラーバーは JS divergence を表す。また、再構成パラメータが (m, τ) のときの JS divergence を $JS(m, \tau)$ として、青い四角は $JS(m, \tau) \leq T$ を満たす (m, τ) の組み合わせである。ここで、 T は閾値であり、 $T = (JS_{\max} - JS_{\min})\theta$ で定義した。ここで、 $JS_{\max}$, $JS_{\min}$ はそれぞれ、 $1 \leq m \leq 20$, $1 \leq \tau \leq 20$ の範囲で得られる 20×20 の JS divergence の値の最大値・最小値である。 θ ($0 \leq \theta \leq 1$) は閾値を決めるパラメータであり、本稿では、 $\theta = 0.1$ とした。

図 1(a), (d), (g) を見ると、再構成次元 m が大きくなるにつれ、小さい時間遅れ τ で JS divergence が小さくなる傾向にあることがわかった。これは、低い再構成次元であっても τ が大きければ適切に状態空間が再構成され、再構成次元 m が大きくなるにつれて比較的小さい τ でも適切に状態空間が再構成されることを意味している。また、これらの結果から、再構成次元 m と時間遅れ τ の積がある小さい任意定数のとき、JS divergence が最小化していると考えられる。したがって、 m と τ の積 $m \cdot \tau$ を W と定義し、 $JS(m, \tau) \leq T$ となる m と τ の組み合わせに対応する W の値を調査した。つまり、JS divergence を最小化する m と τ の組み合わせがどのようなフィッティング関数 $m = W/\tau$ に従うか調査した。具体的には、式 (8) のように W と $JS(m, \tau) \leq T$ となる $m \cdot \tau$ の最小二乗誤差が最小となる W を計算した。

$$\operatorname{argmin}_{(m, \tau) \in E} \sum (m \cdot \tau - W)^2 \quad (W \in \mathbb{Z}) \quad (8)$$

ここで、 $\mathbb{Z}$ は整数集合であり、 E は $JS(m, \tau) \leq T$ を満たす m と τ の組み合わせを要素とする集合である。

図 1(a), (d), (g) から、JS divergence を最小化する m と τ の組み合わせはフィッティング関数によく当てはまっており、変数 x, y, z で W の値は $W = 30, 33, 21$ となった。これらの結果から、アトラクタの幾何学的特徴を再構成するためには、埋め込み窓と呼ばれている $m \cdot \tau$ をある任意定数に保つことが重要であることがわかる。ただし、JS divergence を最小化する埋め込み窓は力学系やデータ長、サンプリングレート、ノイズ量などにも依存するため、観測時系列ごとに個別の議論が必要であり、特に力学系の時間的な相関構造に大きく影響を受けると考えられる。

また、本稿で提案・検討した手法では、真のアトラクタの情報を用いているが、実際の時系列解析の場面では、観測時系列から再構成したアトラクタの情報のみを用いて再構成パラメータ m, τ を推定しなければならない。したがって、再構成アトラクタの 2 点間距離分布に対して、情報量の観点から、適切な m, τ を決める手法を検討する。本稿では、 m, τ を JS divergence の実験と同様に網羅的に変化させて、式 (9) を用いて再構成アトラクタ上の 2 点間距離分布のエントロピーを計算した。

$$H = \sum_{k=1}^N -P_j(k) \log P_j(k) \quad (j \in \{x, y, z\}) \quad (9)$$

再構成アトラクタ上の 2 点間距離分布のエントロピーの結果を図 1(b), (e), (h) に示す。図 1(b), (e), (h) の横軸は再構成次元 m 、縦軸は時間遅れ τ 、カラーバーは再構成アトラクタ上の 2 点間距離分布のエントロピーである。

図 1(b), (e), (h) と図 1(a), (d), (g) を比較すると、JS divergence が最小化した範囲でエントロピーは最大化する傾向にあることがわかった。実際に、JS divergence を最小化する m と τ の組み合わせとエントロピーを最大化する m と τ の組み合わせが対応するか確認するために、JS divergence とエントロピーの差を調査した。その際、JS divergence とエントロピーの範囲を $[0, 1]$ に正規化して差を計算した。具体的には、全ての m, τ の組み合わせで計算した JS divergence $JS(m, \tau)$ の最大値 $JS_{\max}$ 、最小値 $JS_{\min}$ を用いて、 $\hat{JS}(m, \tau) = (JS(m, \tau) - JS_{\min}) / (JS_{\max} - JS_{\min})$ として正規化し、エントロピーも同様の方法で正規化した。図 1(c), (f), (i) に正規化したエントロピーから正規化した JS divergence を引いた結果を示す。

図 1(c), (f), (i) から、エントロピーと JS divergence の差を最大にする m と τ の値の範囲は JS divergence の結果と対応するような傾向が現れた。さらに、変数 x, y の場合は、差の最大値が 1 に近い値のため、エントロピーが最大、つまり 1 に近い値のときに JS divergence が最小、つまり 0 に近い値をとっているといえる。変数 z の場合は、差の最大値が 0.7 程度であるため、JS divergence を最小にする (m, τ) の値の範囲とエントロピーを最大にする (m, τ) の値の範囲は完全には対応しないといえる。これらの結果から、真のアトラクタと再構成アトラクタの 2 点間

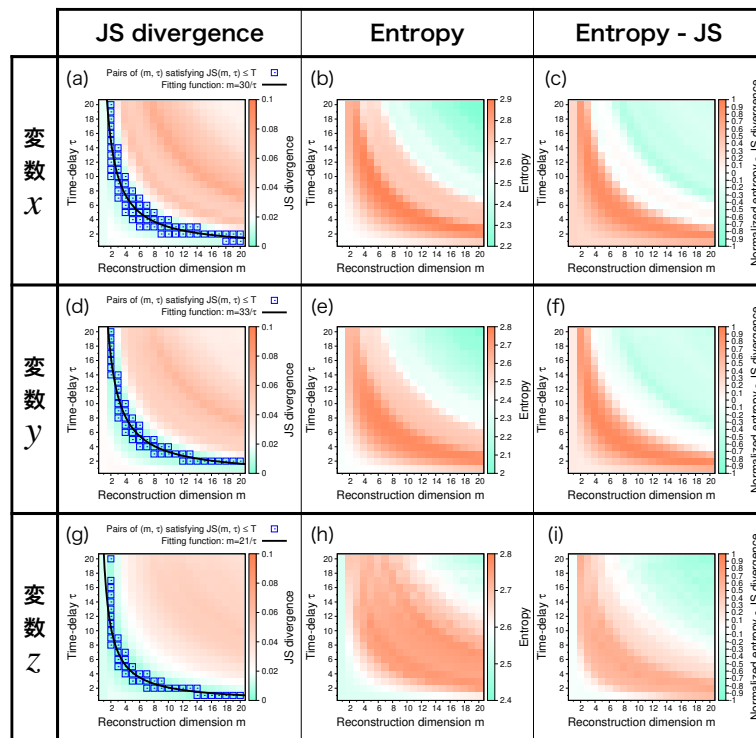


図1 m, τ を変化させた際の Lorenz アトラクタとその再構成アトラクタ上の2点間距離分布間の JS divergence (左列), 再構成アトラクタ上の2点間距離分布のエントロピー (中列), 正規化したエントロピーと JS divergence の差のカラースケール (右列)

距離分布間の JS divergence を最小化する m, τ の組み合わせは、再構成アトラクタ上の2点間距離分布のエントロピーを最大化する傾向があることがわかった。

4. ま と め

本稿では、遅延座標系を用いた再構成の際に適切なパラメータを選択するために、Lorenz 方程式から得た真のアトラクタと再構成アトラクタの2点間距離分布間の JS divergence を計算した。その結果、再構成次元と時間遅れの積が小さい任意定数のとき、JS divergence が最小化することがわかった。つまり、再構成次元と時間遅れの積を一定に保つことで、再構成アトラクタの空間的特徴が真のアトラクタの空間的特徴と類似することがわかった。さらに、再構成アトラクタ上の2点間距離分布のエントロピーを計算した。その結果、JS divergence を最小化する再構成次元と時間遅れの範囲はエントロピーを最大化する再構成次元と時間遅れの範囲と対応することがわかった。

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文 献

- [1] F. Takens, "Detecting strange attractors in turbulence," Dynamical Systems and Turbulence, Vol.898, pp.366–381, 1981.
- [2] T. Sauer, J.A. Yorke, and M. Casdagli, "Embedology," Journal of Statistical Physics, Vol.65, No.3, pp.579–616, 1991.
- [3] P. Grassberger and I. Procaccia, "Characterization of strange attractors," Physical Review Letters, Vol.50, No.5, pp.346–349, 1983.
- [4] J. Lin, "Divergence measures based on the shannon entropy," IEEE

- Transactions on Information Theory, Vol.37, No.1, pp.145–151, 1991.
- [5] J. G. Caputo, B. Malraison, and P. Atten, "Determination of attractor dimension and entropy for various flows: An experimentalist's viewpoint," Dimensions and Entropies in Chaotic Systems, pp.180–190, Springer, 1986.
- [6] D.S. Broomhead and G.P. King, "Extracting qualitative dynamics from experimental data," Physica D: Nonlinear Phenomena, Vol.20, Nos.2–3, pp.217–236, 1986.
- [7] A.I. Mees, P.E. Rapp, and L.S. Jennings, "Singular-value decomposition and embedding dimension," Physical Review A, Vol.36, No.1, pp.340–346, 1987.
- [8] A.M. Albano, J. Muench, C. Schwartz, A.I. Mees, and P.E. Rapp, "Singular-value decomposition and the grassberger-procaccia algorithm," Physical Review A, Vol.38, No.6, pp.3017–3026, 1988.
- [9] P.E. Rapp, A.M. Albano, and A.I. Mees, "Calculation of correlation dimensions from experimental data: Progress and problems," Dynamic Patterns in Complex Systems. World Scientific, pp.191–205, 1988.
- [10] H.S. Kim, R. Eykholt, and J.D. Salas, "Delay time window and plateau onset of the correlation dimension for small data sets," Physical Review E, Vol.58, No.5, pp.5676–5682, 1998.
- [11] P. Grassberger, T. Schreiber, and C. Schaffrath, "Nonlinear time sequence analysis," International Journal of Bifurcation and Chaos, Vol.1, No.3, pp.521–547, 1991.
- [12] J.F. Gibson, J.D. Farmer, M. Casdagli, and S. Eubank, "An analytic approach to practical state space reconstruction," Physica D: Nonlinear Phenomena, Vol.57, Nos.1–2, pp.1–30, 1992.
- [13] M.T. Rosenstein, J.J. Collins, and C.J. De Luca, "Reconstruction expansion as a geometry-based framework for choosing proper delay times," Physica D: Nonlinear Phenomena, Vol.73, Nos.1–2, pp.82–98, 1994.
- [14] D. Kugiumtzis, "State space reconstruction parameters in the analysis of chaotic time series—the role of the time window length," Physica D: Nonlinear Phenomena, Vol.95, No.1, pp.13–28, 1996.
- [15] M. Small and C.K. Tse, "Optimal embedding parameters: a modelling paradigm," Physica D: Nonlinear Phenomena, Vol.194, Nos.3–4, pp.283–296, 2004.
- [16] E.N. Lorenz, "Deterministic nonperiodic flow," Journal of Atmospheric Sciences, Vol.20, No.2, pp.130–141, 1963.

周期入力に対する Izhikevich ニューロンモデルの応答 —Fast Spiking ニューロンの場合—

Responses of the Izhikevich Neuron Model to Periodic Inputs

—In Case of Fast Spiking Neurons—

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1 はじめに

我々は既に、Izhikevich ニューロンモデルが Regular Spiking を呈する際の正弦波入力に対する応答を調査している [1, 2]。その結果、周期応答と準周期応答が発生することを報告した。我々の脳には、興奮性ニューロンと抑制性ニューロンが存在する。抑制性ニューロンは、Izhikevich ニューロンモデルの Fast Spiking (FS) ニューロンとして再現可能である。そこで本稿では、抑制性ニューロンの一つである FS ニューロンの周期入力に対する応答を調査したので報告する。

2 数値実験

本稿では、Izhikevich ニューロンモデル [3] のパラメータを FS ($a = 0.1, b = 0.2, c = -65, d = 2$) に設定する。数値計算にはオイラー法 (時間ステップ 0.01) を用いて、発火時刻を線形内挿により推定した [4]。また、周期入力を正弦波 $I(t) = I_{DC} + I_{AC} = I_{DC} + A \sin(2\pi/T)t$ とする。 $I_{DC} = 10$ とし、 I_{AC} の振幅 A 、周期 T を変化させた際の、Izhikevich ニューロンモデルの応答を定量的に調査した。評価には、ISI (Interspike Interval) に対する多様性指数 $R = m/n$ [5, 6] を用いた。ただし、ISI の総数を n 、ISI の種類数を m とする。周期応答 ($n \gg m$) の場合、 $R \approx 0$ となる。また、非周期応答 ($n \approx m$) の場合、 $R \approx 1$ となる。本稿では、ISI を小数第 10 位までの精度とした。時刻 $0 \leq t < 5,000$ を過渡状態として排除し、 $5,000 \leq t \leq 15,000$ の発火時系列から多様性指数を計算した。正弦波の振幅を $0 \leq A \leq 10$ 、周期を $1 \leq T \leq 1,000$ の範囲で変化させ、多様性指数を調べた結果を図 1 に示す。図 1 の横軸と縦軸は正弦波の周期 T と振幅 A 、カラーバーは多様性指数の値である。周期応答の領域と非周期応答の領域は、 T が大きくなるにつれて $A = 6$ 付近に収束していることが分かる。

次に、非周期応答となる場合について、ストロボ観測点を用いて調査した。図 1 で $A = 2.5$ 、 $T = 200$ と設定した場合 ($R = 1$) のストロボ観測点を図 2 に示す。横軸と縦軸は Izhikevich ニューロンモデルの膜電位 v と回復変数 u である。図 2 より、曲線が出現することが分かる。即ち、アトラクタはトーラスであり、応答は準周期的である。本来、アトラクタがトーラスの場合は、閉曲線がプロットされるが、Izhikevich ニューロンモデルは瞬時リセットを含むため、閉曲線とならない。

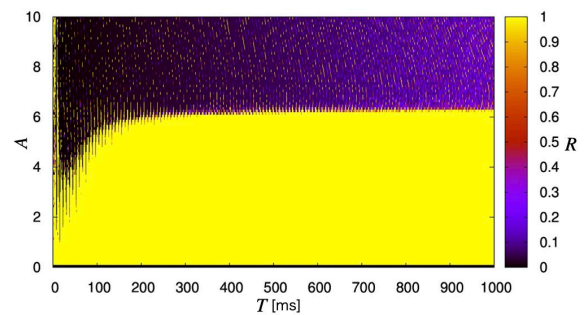


図 1: Izhikevich ニューロンモデル (FS) の多様性指数 R の結果

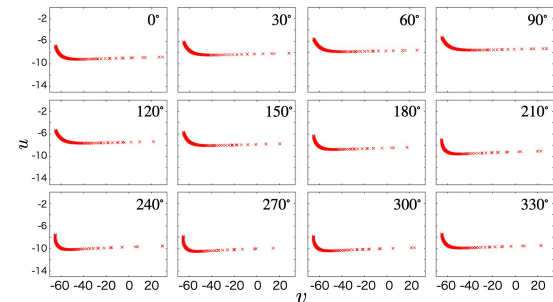


図 2: 非周期応答 ($A = 2.5$, $T = 200$) の場合のストロボ観測点

3 まとめ

本稿では、Izhikevich ニューロンモデルが FS ニューロンとなる場合の正弦波入力に対する応答を調査した。多様性指数を用いた調査により、周期応答と非周期応答の存在を確認した。また、ストロボ観測点を用いた解析により、非周期応答が準周期応答であることが分かった。なお、本研究の一部は、JSPS 科研費 JP20H000596, JP21H03514 の助成を受けた。

参考文献

- [1] Tsukamoto et al., *NLSW2021*, NLSW-54, 2021.
- [2] Tsukamoto et al., submitted to *NOLTA*, *IEICE*, 2021.
- [3] Izhikevich, *IEEE TNN*, 14(6), 1569–1572, 2003.
- [4] Izhikevich, *Phil. Trans. R. Soc. A*, 368(1930), 5061–5070, 2010.
- [5] 杉浦 他, 信学技報, 113(116), 43–48, 2013.
- [6] 内木 他, 信学論 A, J100-A(5), 195–204, 2017.

マーク付点過程に対する重み付き Visibility Graph

A Study on Weighted Visibility Graph for Marked Point Processes

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1 はじめに

時系列を複雑ネットワークに変換して解析する手法の 1 つに Visibility Graph (VG) 法 [1] がある。従来の VG 法では、その多くがデータの時間間隔が一定である時系列 (Equally sampled Time Series, 以下 ETS) に対して適用されている [2]。しかし、実世界のデータの多くは、時間間隔が一定ではないマーク付点過程 (Marked Point Process, 以下 MPP) として観測される。即ち、VG 法の MPP への適用可能性を検討することも重要である。例えば、地震情報の MPP と、その時間間隔を一定にした ETS に対して VG 法を適用すると、得られたネットワークの解析結果が類似することも報告されている [3]。これはネットワークに変換した際に MPP の時間間隔情報が欠落したためである。そこで本稿では、VG 法を MPP に適用する際、時間間隔情報をどのようにネットワークに反映すべきかについて検討した結果を報告する。

2 実験手法

本稿では、MPP を修正ベルヌーイ写像 [4] より作成した。具体的には、以下の 2 種類の手法により作成する。1 つ目の手法では、修正ベルヌーイ写像の値を作成する MPP の時間間隔に割り当てる手法である (Values to Inter Event Interval, 以下 V-IEI)。修正ベルヌーイ写像の時刻 n における状態値を $x(n)$ とすると、作成する MPP の i 番目のイベント発生時刻 t_i は $t_i = \sum_{j=1}^i x(j)$ となる。2 つ目の手法では、修正ベルヌーイ写像の状態値 $x(n)$ と $x(n+1)$ を接続する線が 0.5 と交わる時刻を MPP のイベント発生時刻とする (内挿)。いずれの手法においても作成した MPP のデータ数は 2,000 とし、マーク値 m_i は区間 $[0, 1]$ の一様乱数で決定した。また、各手法を用いて 100 個の MPP を作成した後、各 MPP のマーク値が同じで時間間隔を 1 とした ETS を作成する。作成した MPP と ETS に対し、VG 法を用いて重み付きネットワークを作成した。

本稿では、MPP の i 番目のイベントがネットワークにおける頂点 v_i となる。その際、MPP 上での i 番目のイベントと j 番目のイベント間距離 $l_{ij} = \sqrt{(t_i - t_j)^2 + (m_i - m_j)^2}$ を用いて、頂点 v_i, v_j 間の重みを決定した。具体的には $w_{ij} = l_{\min}/l_{ij}$ とした。なお、重みを $w_{ij} = l_{ij}/l_{\max}$ とした場合 [5] の結果と比較した。ただし、 $l_{\max}$, $l_{\min}$ は l_{ij} の最大値、最小値である。

3 実験結果

解析に使用したネットワーク構造を定量化する指標として、重み付き平均頂点間距離 L_w [6] と 4 種類の重み付きクラスタ係数 $C_w^{(Z)}, C_w^{(L)}, C_w^{(B)}, C_w^{(O)}$ [7-10] を用い

た。本稿では、 $L_w, C_w^{(Z)}$ の平均値を 95%信頼区間と共に示す (表 1, 2)。

表 1: 提案法を時系列に適用した結果

手法	時系列	L_w	$C_w^{(Z)}$
V-IEI	MPP	0.033±0.003	0.011±0.001
	ETS	0.988±0.003	0.373±0.000
内挿	MPP	0.281±0.003	0.152±0.001
	ETS	0.988±0.003	0.373±0.000

表 2: 文献 [5] の手法を時系列に適用した結果

手法	時系列	L_w	$C_w^{(Z)}$
V-IEI	MPP	0.747±0.045	0.007±0.004
	ETS	0.813±0.044	0.005±0.000
内挿	MPP	0.765±0.045	0.003±0.004
	ETS	0.823±0.044	0.005±0.000

表 1, 2 より、提案法を適用した場合、 L_w と $C_w^{(Z)}$ において MPP と ETS から作成されるネットワークの間には有意差があることが分かる。この傾向は $C_w^{(B)}$ 以外のクラスタ係数でも同様であった。一方、文献 [5] の重み付けを用いた場合、 L_w と $C_w^{(Z)}$ において MPP と ETS から作成したネットワークの間に有意差はない。これらの結果から、提案法は MPP の時間間隔情報を適切に重み付きネットワークに反映できていると考えられる。

4 まとめ

本稿では、修正ベルヌーイ写像を用いて MPP を作成した。次に、得られた MPP を重み付きネットワークに変換する手法を提案した。その結果、提案法を適用することで、MPP の時間間隔情報がネットワーク構造に反映されることがわかった。なお、本研究の一部は、JSPS 科研費 JP19K14589, JP20H00596, JP21H03514 の助成を受けたものである。

参考文献

- [1] L. Lacasa, et al., *PNAS*, **105**, 13, 4972–4975, 2008.
- [2] J. B. Elsner, et al., *Geo. Res. Lett.*, **35**, 16, 2009.
- [3] B. Aguilar-San Juan, and L. Guzman-Vargas, *E. Phys. J. B*, **86**, 11, 1–10, 2013.
- [4] Y. Aizawa, and T. Kohyama, *PTP*, **71**, 4, 847–850, 1984.
- [5] M. Zhang, et al., *Sci. Rep.*, **11**, 1, 1–12, 2021.
- [6] X. J. Xu, et al., *Int. J. Mod. Phys. C*, **17**, 04, 521–529, 2006.
- [7] B. Zhang, and S. Horvath, *Stat. Anal. Gen. Mol. Biol.*, **4**, 1, 2005.
- [8] L. Lopez-Fernandez, et al., *Proc. of 1st Int. Workshop on MSR 2004*, 101–105, 2004.
- [9] A. Barrat, et al., *PNAS*, **101**, 11, 3747–3752, 2004.
- [10] J. P. Onnela, et al., *PRES*, **71**, 6, 065103, 2005.

Colexification ネットワークにおける感情とハブ

Emotions and hubs in a network of colexification

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1 はじめに

近年 colexification に基づく感情分類の研究が注目を集めている [1]. colexification とは単一の単語が複数の概念を意味する現象である [2]. 例えばスペイン語において, “malo” という単語は “BAD (悪い)” と “SEVERE (厳しい)” の二つの概念を意味し, colexification を呈する. ある言語において, colexification を呈する複数の概念は意味が類似する傾向にある. このような観点から, 概念を頂点, 2つの概念から colexification を呈する言語の数を枝の重みとした重み付きネットワーク (図1) を用いることで, 概念間の類似性に基づいた言語の特徴を調べる研究が行われている [1].

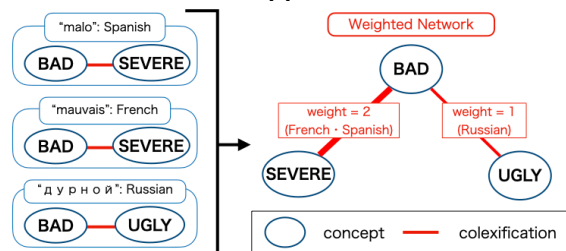


図1: colexification ネットワークの作成例

文献 [1] では, このような colexification ネットワーク上でランダムウォークを適用した際の, 任意の頂点ペア間における n ステップ後の遷移確率を求めることで, 感情を表す概念間の類似性を調査している. しかし, 文献 [1] では $n = 1, \dots, 5$ の場合しか考慮されていない. そこで本稿では, ステップ数 n を増やした際の, ネットワークの構造の変化について調査した結果を報告する.

2 ネットワークの作成法

まず, 文献 [1] と同様に, 3,061 の言語における colexification を収録したデータベース CLICS³ [2] を用いて, colexification ネットワークを作成する. ここで, 頂点 i と j を繋ぐ枝の重みを W_{ij} とする. 次に, ランダムウォークを用いて隣接していない概念間の間接的な繋がりを考慮したネットワークを作成する. ランダムウォークは枝で繋がる頂点間を遷移確率行列 $P = [P_{ij}]$ に基づいて移動する手法である. ここで, $P_{ij} = W_{ij} / \sum_{k=1}^N W_{ik}$, N を頂点数とする. また, n ステップ後の遷移確率行列を P^n とする. 文献 [1] では, $B^{(n)} = \sum_{s=1}^n P^s$ を重み付き隣接行列とするネットワークから, 代表的な感情の概念と, その概念を繋ぐ枝のみを抽出したネットワーク $C^{(n)}$ を作成している. その際, 全ての頂点ペア (i, j) に対して $C_{ij}^{(n)} \neq 0$ を満たす n の最小値が5であったことから, $C^{(5)}$ で表されるネットワークにおける, 感情を表す概念のコミュニティ構造を調査している. しかし, $n = 5$ の場合, 感情を表す概念間を繋ぐ経路に現れる頂点 (概念) の数は高々5つであり, 6 ステップ以上離れた頂点 (概念) の影響は考慮されていない.

3 数値実験

本稿では, 感情を表す概念間を繋ぐ経路上に現れる, 感情以外を表す概念に対応する頂点の数を増加させるため, ランダムウォークのステップ数を 1,000 まで増加させた. また, 作成するネットワークにおいてステップ数を増やした結果を枝の重みに反映させるため, P^n を重み付き隣接行列とするネットワークを作成した. また, P^n から代表的な感情の概念と, その概念を繋ぐ枝のみを抽出したネットワーク $Q^{(n)}$ を作成した. 作成したネットワーク $Q^{(n)}$ を図2の上段に, ネットワーク $Q^{(n)}$ における枝の重みの分布を下段に示す.

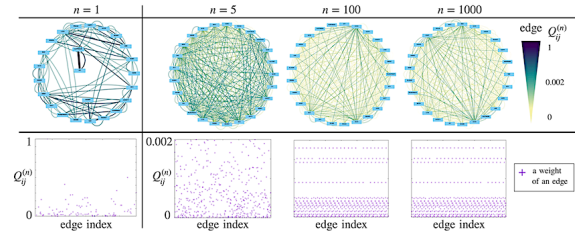


図2: ネットワーク $Q^{(n)}$ と枝の重み分布

図2から, n の増加に伴ってネットワークの枝の重みが一定値に収束する傾向が見られる. また, 図2下段より, $Q^{(n)}$ において同じ重みを持つ枝の集合が存在していることがわかる. どのような枝が集合を構成するかを確認したところ, 同じ頂点に向かう枝であることがわかった. また, 重みの大きい順に “GOOD”, “WANT”, “BAD”, “LOVE” であること, これらの4つの頂点に向かう枝の重みは, 他の枝の重みに比べて大きいことを確認した. さらに, これらの4つの頂点は, 感情を表す概念のうち, 感情以外を表す概念に対応する, より多くの頂点と隣接していることも確認した. ネットワークにおいて, 他の頂点と比べて隣接する頂点が多い頂点はハブと呼ばれることから, これらの4つの頂点は, colexification ネットワークにおいてハブであることが示された.

4 まとめ

本稿では, colexification ネットワークを作成する際に用いるランダムウォークのステップ数を増加させることで生じる, ネットワーク構造の変化について調査した. その結果, colexification ネットワークにおいて, ハブとなっている感情を表す概念に対応する頂点が存在することが確認された.

本研究の一部は, JSPS 科研費 JP21H03514, JP20H00596, JP19K01653, JP18K12701, JP21H03508 の助成を受けたものである.

参考文献

- [1] J. C. Jackson, et al., *Science*, Vol. 366, No. 6472, pp. 1517–1522, 2019.
- [2] J. M. List, et al., <https://clics.clld.org/>, (Last visit Dec. 3rd, 2021).

脈波データを用いた再構成パラメータの設定について

A study on reconstruction parameters for transforming photoplethysmogram into time-delay coordinate system

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1 はじめに

観測時系列を遅延座標系に変換し、非線形力学系のアトラクタを再構成する手法は、力学系の特性を把握する上で必要不可欠である [1, 2]。しかし、遅延座標系を用いる際には、適切な再構成次元と時間遅れを設定する必要がある。特に、実データを解析する際は、必要十分かつ可能な限り小さい再構成次元と可能な限り小さい時間遅れが望ましい。我々は既に、数理モデルの真のアトラクタと観測時系列から再構成したアトラクタ上の2点間距離分布間の距離を計算することで適切な再構成パラメータを推定する手法を提案している [3]。また、再構成アトラクタ上の2点間距離分布のエントロピーを最大化する再構成パラメータは、真のアトラクタと再構成アトラクタ上の2点間距離分布間の距離を最小化する再構成パラメータと概ね一致することも示している [4]。本稿では、人の指先から計測した脈波データ [5, 6] に対して、再構成次元、時間遅れを変化させ、再構成アトラクタ上の2点間距離分布のエントロピーを計算し、適切な再構成パラメータの検討を行ったので報告する。

2 解析対象データ

本稿では、人の指先からパルスオキシメータ (東京デバイス 汎用心拍センサ IWS920 開発キット「パルス・ラボ」 [7]) によって LED 光を用いて非侵襲に計測した光電脈波の時系列データを解析対象とした。その際、「東京理科大学 人を対象とする医学研究の実施及び倫理に関する規定」に従い、実験手順などを被験者に十分説明し、同意を得たのちに室温約 24 °C の快適な環境下かつ安静状態で約 5 分間計測した。また、本稿で用いたデータは、22 歳の健康な女性のデータであり、計測時のサンプリング間隔は 1/409.6 秒、解析に使用した時系列データのサンプリング間隔は 10/409.6 秒とした。

3 数値実験

本稿では、脈波データを遅延座標系に変換する際、再構成次元 m 、時間遅れ τ を 1~30 の範囲で変化させ、再構成アトラクタ上の2点間距離分布のエントロピーを計算した [4]。その際、データ点数は 5,000 点用い、2点間距離分布の階級数は、Freedman-Diaconis の法則に従って決定した [8]。結果を図 1 に示す。図 1 から、時間遅れ τ が比較的小さい領域では、エントロピーは小さい値となっている。一方、時間遅れ τ が大きくなるにつれて、エントロピーは大きい値となっている。

4 まとめ

本稿では、人の指先から計測した脈波の時系列データを遅延座標系に変換する際、再構成パラメータを網羅的

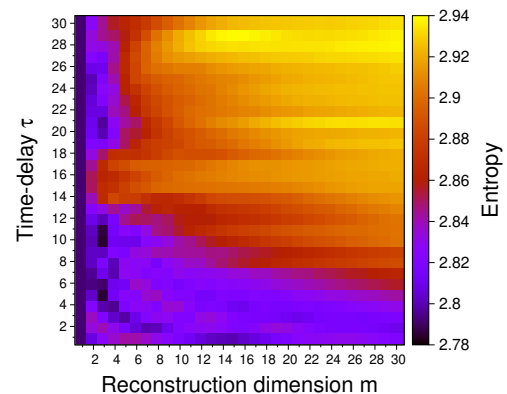


図 1 再構成次元、時間遅れを変化させた際の再構成アトラクタ上の2点間距離分布のエントロピー

に変化させ、再構成アトラクタ上の2点間距離分布のエントロピーを計算した。その結果、時間遅れ τ が小さい範囲では、エントロピーが比較的小さい値を取り、時間遅れ τ が大きい範囲では、エントロピーが比較的大きい値を取ることがわかった。

本研究の一部は、JSPS 科研費 (Nos. JP19K14589, JP20H00596, JP21H03508, JP21H03514) の援助を受けて行われた。

参考文献

- [1] F. Takens, in *Dynamical Systems and Turbulence*, eds. D. A. Rand and L.-S. Young, **898**, 366–381, 1981.
- [2] T. Sauer, et. al., *Journal of Statistical Physics*, **65**, 3, 579–616, 1991.
- [3] K. Sawada, et. al., submitted to *NOLTA, IEICE*, 2021.
- [4] 澤田 他, 信学技報, **121**, 307, 96–99, 2021.
- [5] I. Tsuda, et. al., *International Journal of Bifurcation and Chaos*, **2**, 2, 313–324, 1992.
- [6] N. Sviridova and K. Sakai, *Chaos, Solitons & Fractals*, **77**, 53–63, 2015.
- [7] 東京デバイス 汎用心拍センサ IWS920 開発キット「パルス・ラボ」<https://tokyodevices.com/items/188> [accessed 2021/12/21].
- [8] D. Freedman and P. Diaconis, *Zeitschrift für Wahrscheinlichkeitstheorie und verwandte Gebiete*, **57**, 4, 453–476, 1981.

ユーザ属性に着目した バイクシェアリングシステム利用履歴データの解析

Analysis on usage history with user attribute in a bicycle sharing system

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1 まえがき

バイクシェアリングシステム (BSS) で生じる自転車の過不足台数を調整するために、我々は複数の自転車回収車を用いた自転車再配置問題の提案とその問題に対する発見的解法の開発に取り組んでいる [1, 2]. その際、ランダムにポートを配置したオリジナルの問題例を用いて、性能評価を行ったが、実際の BSS における再配置作業の効率的な戦略を提案するためには、実際のポート配置や利用履歴情報を組み込むことが重要となる. そこで我々は、BSS の実際の利用履歴データを点過程と捉えることで解析を行い、平日と週末の利用パターンに差がないことなどを明らかにした [3, 4]. 実際の BSS では、様々なユーザ属性が利用履歴と併せて記録されている. そこで本稿では、ユーザ属性の中でも特に定期所有情報に着目することで利用履歴を解析した結果を報告する.

2 統計的な解析

本稿では、2017 年のシカゴ [5] の利用履歴データを解析した結果を報告する. 利用履歴データには、自転車を借りたポートの ID と日時、返却したポートの ID と日時、ユーザ属性が含まれる. ユーザー属性は定期利用、非利用の 2 種類がある. 本稿では、自転車の貸出と返却が行われた時間を点過程として扱い、ラスタプロット、変動係数 (C_V)、局所変動係数 (L_V) を用いて、各ポートにおける自転車の貸出と返却のイベントの発生パターンがどのように振舞うか調査した. C_V と L_V を求めるために、まず、inter-event-intervals (IEIs) を求める. あるポートで i 番目にイベントが発生した時間を t_i 、次にそのポートでイベントが発生した時間を t_{i+1} とする. i 番目の IEI を $T_i = t_{i+1} - t_i$ と定義すると、IEI を用いて、 C_V , L_V は $C_V = \sqrt{1/(n-1) \sum_{i=1}^n (T_i - \bar{T})^2 / \bar{T}}$, $L_V = 1/(n-1) \sum_{i=1}^{n-1} 3(T_i - T_{i+1})^2 / (T_i + T_{i+1})^2$ と定義される. n は IEI の数を示し、 $\bar{T}$ は IEI の平均を示す. C_V は全ての IEI の変動を示し、 $C_V = 0$ であれば、自転車の貸出・返却の発生は規則的に発生していることを示す. 一方、 $C_V = 1$ であれば、ポアソン過程となる. また、 L_V とは、局所的な変動を測る指標である、 $L_V = 0$ であれば自転車の貸出・返却の発生は規則的に発生し、 $L_V = 1$ であれば、IEI はポアソン過程となる.

はじめに、8 月の第一水曜日 (平日) と第一土曜日 (週末) の貸出ラスタプロットを図 1 に示す. 横軸は時間 (分) を示し、縦軸はポート ID を示している. 図 1 より、定期利用者の平日の利用パターンは朝夕の通勤時間帯に多くの自転車が利用され、週末は通勤の時間帯にはピークがないパターンであることわかる. 一方、定期非利用者は平日、週末共に通勤の時間帯にピークはなく、昼す

ぎから利用が増加する傾向にある. 次に、表 1, 2 に、 C_V , L_V の平均値 μ_C , μ_L の 95% 信頼区間を示す. 表 1 より、平日、週末共に、ユーザ属性を考慮しない場合、定期利用、定期非利用の全てについて 1 より大きい値をとっている. 一方、表 2 より、ユーザ属性を考慮しない場合と定期利用の場合は、平日、週末全て 1 に近づき、特に、定期利用の場合は、1 に近い値を取ることがわかった.

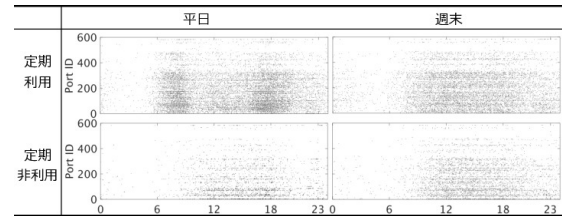


図 1 ラスタプロット

表 1 C_V の信頼区間

	平日	週末
ユーザ属性考慮なし	$1.64 \leq \mu_C \leq 1.75$	$1.62 \leq \mu_C \leq 1.72$
定期利用	$1.66 \leq \mu_C \leq 1.77$	$1.48 \leq \mu_C \leq 1.56$
定期非利用	$1.36 \leq \mu_C \leq 1.45$	$1.59 \leq \mu_C \leq 1.71$

表 2 L_V の信頼区間

	平日	週末
ユーザ属性考慮なし	$1.11 \leq \mu_L \leq 1.16$	$1.23 \leq \mu_L \leq 1.28$
定期利用	$1.08 \leq \mu_L \leq 1.12$	$1.15 \leq \mu_L \leq 1.19$
定期非利用	$1.63 \leq \mu_L \leq 1.71$	$1.63 \leq \mu_L \leq 1.71$

3 まとめ

本稿では実際の BSS の利用パターンについてユーザ属性に着目した解析を行った. その結果、ラスタプロットから定期利用者と定期非利用者の自転車の利用パターンは異なること、また、局所変動係数の結果から、定期利用者の平日の自転車の利用パターンは 1 に近い値を取ることがわかった. 本研究の一部は、JSPS 科研費 JP20H000596, JP21H03514 の援助を受けた.

参考文献

- [1] H. Tsushima, et al., *J. of Signal Processing*, **22**(4), pp. 157–160, 2018.
- [2] H. Tsushima et al., *App. Sci.*, **11**(16), 7749, 2021.
- [3] H. Tsushima et al., *NLSW2021*, NLSW-32, 2021.
- [4] H. Tsushima et al., submitted to *NOLTA, IEICE*, 2021.
- [5] Divvy system data.
<https://www.divvybikes.com/system-data>.

学位論文

修士論文要旨

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論文提出者 情報工学専攻 ジョ ロエン

論文題目 Research of Information Diffusion on Complex Networks

複雑ネットワーク上での情報拡散に関する研究

本論文では、まず情報への関心度に着目した情報拡散モデルを提案し、Centola の社会実験を再現するための数値実験を行った。その結果、Centola の社会実験の結果と同様に、格子ネットワーク上ではランダムネットワーク上よりも情報が広く拡散することを明らかにした。次に、従来の情報拡散モデルを分類し、従来モデルと比較することで我々の提案するモデルの位置づけを明らかにした。さらに、格子ネットワークとランダムネットワーク上での情報拡散について、拡散の広さと速さの解析を行った。その結果、情報の影響力が極めて大きい場合、格子ネットワークよりもランダムネットワーク上の方が情報が拡散しやすいことが示唆された。

一方、現実世界における情報拡散は動的であるため、構造が動的に変化するテンポラルネットワーク上での情報拡散の解析も必要である。そこで本論文では、数値実験によりテンポラルネットワーク上での情報拡散の解析も行った。まず、SocioPatterns での高校と病院のコンタクトデータからテンポラルネットワークを生成した。次に、静的ネットワーク用の情報拡散モデルを元に、テンポラルネットワークに対する新しい情報拡散モデルを提案した。その後、テンポラルネットワーク上での情報拡散の広さについて解析を行った。その結果、テンポラルネットワーク上での情報拡散は、コンタクトの密度に関係することがわかった。次に、コンタクトの密度を変化させ、コンタクトのサロゲートデータを作成した。その後、コンタクトの密度が情報拡散に与える影響を、生成したサロゲートデータを用いて調査した。その結果、コンタクトの密度が高い場合、情報が広く拡散することが示唆された。また、コンタクトの密度以外に、情報拡散に影響を与える要素が多く存在している。従って、本論文では三つの手法を用いて、コンタクトの順番を変化させ、コンタクトのサロゲートデータを3種類作成した。その後、コンタクトの順番が情報拡散に与える影響を、生成した三つのサロゲートデータを用いて調査した。その結果、情報への関心度の減衰が強い場合、中心性の高いコンタクトの順番が情報拡散に強く影響することも示唆された。一方、情報への関心度の減衰が弱い場合、コンタクトの順番が情報拡散に弱い影響を与えることは示唆された。

修士論文要旨

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論文題目 Research of Information Diffusion on Complex Networks
複雑ネットワーク上での情報拡散に関する研究

In this thesis, we firstly proposed an information diffusion model which focuses on the interest in information, and conducted a numerical experiment to reproduce Centola's experiments. As a result, we found that information spreads more widely on lattice networks than on random networks as well as the findings of Centola's experiments. We analyzed the influence of network structure on the extent and the speed of information diffusion using lattice networks and random networks. As a result, we found that if the information is influential, information is easier to be spread on the random networks than on the lattice networks.

Furthermore, information diffusion in the real life is dynamic, which means that we have to analyze the temporal networks whose structure changes dynamically. Therefore, we also analyzed the information diffusion on temporal networks through numerical experiments. We firstly generated temporal networks from the face-to-face contact data of a high school and a hospital in SocioPatterns. Then, we proposed a new information diffusion model for temporal networks modified by the proposed model on static networks. After that, we analyzed the extent of information diffusion on the temporal networks. We found that information diffusion on the temporal networks is related to the contact density.

Then, we generated surrogate contact data with different contact density. After that, we investigated the influence of contact density using this surrogate data. As a result, we found that information spreads widely when the contact density is high. In addition to the contact density, there are many other factors that affect the information diffusion. Then, we generated surrogate contact data with different contact order using three methods. We investigated the influence of contact order on information diffusion using three surrogate data, respectively. Moreover, we also found that if the decay of interest in information is strong, the order of vertices with high centralities strongly affects the information diffusion. In contrast, if the decay of interest in information is weak, the contact order weakly affects the information diffusion.

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論文題目 Solution Space Reduction Methods for Combinatorial Optimization Problems

組合せ最適化問題の解空間削減手法

現在研究が活発に行われている組合せ最適化問題の多くは $\mathcal{NP}$ 困難であることが知られている。 $\mathcal{NP}$ 困難な問題は現実的な時間で最適解を求めることは難しいと考えられている。そのため、最適解に近い解を効率的に求める発見的解法が様々な分野から研究されている。しかし、近年では非常にサイズの大きい問題や制約が複雑な問題を解くことが求められている。高性能な発見的解法を用いても、サイズの大きい問題や制約が複雑な問題の解を求めるためには多大な計算時間を必要とする。

発見的解法の計算時間を短縮する方法の 1 つとして、発見的解法で探索する不要な解の構成要素 (枝) を削減する手法がある。最も研究されている組合せ最適化問題の 1 つである巡回セールスマン問題 (TSP) では既に枝候補の削減手法が研究されており、サイズの大きい問題を解決するためには枝候補の削減が重要であることが示されている。

そこで本論文では従来の TSP の枝候補削減手法を改良した。数値実験の結果、提案手法は発見的解法による解の性能を維持しつつ計算時間を短縮した。削減された枝候補について詳細な調査を行ったところ、提案手法は従来手法よりも多くの不要な枝を削減しつつ必要な枝を正確に残していることがわかった。これにより、枝候補の削減手法は発見的解法の性能に大きく影響を与えることが示された。

また、多くの組合せ最適化問題では枝候補の削減方法についてあまり議論がされていない。本論文では、時間情報の含まれる時間窓付き配送計画問題 (VRPTW) に対して新たに枝候補の削減手法を提案した。数値実験の結果、枝候補の削減は VRPTW に対しても TSP と同様に有効であることを確認した。枝候補削減の際のパラメータについて詳細な調査を行った結果、時間情報が重要な VRPTW でも枝候補削減の際に時間情報は不要であることが示された。このことから、VRPTW 以外の組合せ最適化問題に対しても提案手法による枝候補の削減は有効である可能性が示唆された。

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論文題目 Solution Space Reduction Methods for Combinatorial Optimization Problems

組合せ最適化問題の解空間削減手法

Many of the combinatorial optimization problems are known to be $\mathcal{NP}$ (Non-deterministic Polynomial-time)-hard. $\mathcal{NP}$ -hard problems are considered to be challenging to find the optimal solution in polynomial time using modern computers under the $\mathcal{P} \neq \mathcal{NP}$ expectation. It is not easy to find the optimal solution in real-time. For this reason, many researchers study heuristic methods for efficiently finding near-optimal solutions. However, in recent years, there has been a need to solve problems with very large sizes and complex constraints. Even with high-performance heuristic methods, it takes a lot of computation time to solve large problems or problems with complex constraints.

One way to reduce the computational time of heuristic solution methods is to reduce the number of unnecessary solution components (edges). Edge reduction methods have already been studied for the Traveling Salesman Problem (TSP), one of the most studied combinatorial optimization problems. The research shows that edge candidate reduction is important for solving large-size TSP.

This thesis improves the conventional edge candidate reduction method for TSP. Numerical experiments show that the proposed method reduces the computational time while maintaining the performance of the heuristic solution. A detailed study of the reduced edge candidates shows that the proposed method reduces unwanted edges than the conventional method while retaining the necessary edges. This indicates that the edge candidate reduction method has a significant impact on the performance of the heuristic solution method.

In addition, there is not much discussion on edge candidate reduction methods in many combinatorial optimization problems. This thesis proposes a new edge candidate reduction method for the Vehicle Routing Problem with Time Windows (VRPTW) with temporal information. Numerical experiments show that the edge candidate reduction is as effective for VRPTW as for TSP. As a result of the detailed investigation on the parameters of edge candidate reduction, it is shown that temporal information is not necessary for edge candidate reduction, even for VRPTW, where temporal information is important. This suggests that the edge candidate reduction by the proposed method may be effective for combinatorial optimization problems other than VRPTW.

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論文題目 Multilingual Analysis Based on Word Co-occurrence Using Complex Network Theory
複雑ネットワーク理論を用いた単語の共起に基づく多言語解析

共起数 2 の単語の共起ネットワーク (Word Co-occurrence Network, WCN) を用いたこれまでの研究は、言語の構造的特徴の一部しか解析できていないという問題が残されている。そこで本論文では、多言語から作成した WCN の構造的特徴を二つの観点から検討した。第一に、共起数 2 の WCN では反映されていなかった言語の特徴を捉えるため、共起数を増加させた際の WCN の構造的特徴の変化を調査した。第二に、WCN の構造的特徴に対する文書内容の影響を調査するため、異なる文書から作成した WCN の構造的特徴を比較した。これらの解析を行うために、九種類の言語で翻訳されている四種類の異なるテキストデータ-新約聖書、国連議事録、パリ協定、小説-を用いた。

本論文では主に、三つの実験を行なった。第一に、使用したテキストデータと WCN の基本情報を調査した。具体的には、単語数と頂点数の関係、文章中とネットワーク内の品詞の割合、WCN 解析における読点の影響、フレーズ内の単語数、枝数、密度、累積次数分布である。第二に、単語の使用頻度が WCN の構造的特徴に反映されているかを調査した。具体的には、単語の使用頻度と六つのネットワーク指標 (次数中心性、近接中心性、媒介中心性、固有ベクトル中心性、クラスタ係数、四角形クラスタ係数) の相関係数を調査した。第三に、共起数を増加させた際の WCN の構造的特徴を調査した。具体的には、クラスタ係数、四角形クラスタ係数、平均頂点間距離、品詞のペア間のつながりを用いた。

本論文の結論は二つである。第一に、共起数を増加させることで、共起数 2 の WCN では反映されない特徴を捉えることができることがわかった。特に、膠着語である日本語とフィンランド語の特徴を抽出できることが示された。これは、共起数を増やした WCN を用いた言語解析が、多言語の共通点や相違点を明らかにするための有望なアプローチであることを示唆する結果である。第二に、ネットワーク指標によって、文書内容に依存する場合があるということがわかった。これは、解析に使用するテキストデータは、言語解析において重要な要素であることが示唆するものである。

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論文題目 Multilingual Analysis Based on Word Co-occurrence Using Complex Network Theory
複雑ネットワーク理論を用いた単語の共起に基づく多言語解析

Previous studies using word co-occurrence networks (WCNs) with the number of connected words equals two could only analyze a part of the structural features of languages. Therefore, in this thesis, we examined the structural features of WCNs from two perspectives. First, to capture the features of languages that cannot be reflected in the WCNs when the number of connected words is two, we conducted a multilingual analysis by investigating the changes in the structural features of WCNs when the number of connected words increases. Second, to investigate the effect of document content on the structural features of WCNs, we compared the structural features of WCNs created from different documents. To perform these analyses, we used four different text datasets translated into nine different languages: the New Testament of the Christian Bible, the United Nations proceedings, the Paris Agreement, and the Novels.

We conducted mainly three experiments. First, we investigated the basic information of the text data we used and the WCNs. More specifically, we calculated the relationship between the number of words and the number of vertices, the frequency of parts of speech in sentences and WCNs, the effect of punctuation marks on the WCN analysis, the length of a phrase, the number of edges, the density, and the cumulative degree distribution. Second, to investigate whether the structural features of WCNs reflect the frequency of words, we calculated the correlation coefficient between the frequency of words and six network measures: the degree centrality, the closeness centrality, the betweenness centrality, the eigenvector centrality, the clustering coefficient, and the square clustering coefficient. Third, we investigated the structural features of WCNs when the number of connected words n increases and the connections between pairs of parts of speech.

Our conclusions are two folds. First, by increasing the number of connected words, we can capture the features of languages that cannot be reflected WCNs when the number of connected words equals two. In particular, agglutinating languages (Japanese and Finnish) have different structural features of WCNs from the other languages. Therefore, we suggest that multilingual analysis using WCNs with increasing the number of connected words is a promising approach to clarify the commonalities and differences among languages. Second, we found that some network measures depend on the document content. Hence, text data used in the analysis is an important factor in multilingual analysis.

非線形時系列解析を用いた生体情報抽出に必要な光電脈波時系列長の調査

荒井頌太 (池口 徹 教授 , Nina Sviridova 助教)

1 はじめに

光電脈波 (Photoplethysmogram, 以下 PPG) は, 非侵襲に測定可能な心血管系の生体信号である [1]. PPG は比較的安価な計測機器によって計測できるため, 医療現場やスマートウォッチなどのウェアラブルデバイスに導入可能である. PPG データは, 主に心拍数や血圧, メンタルヘルスなど, 人間の心身の健康状態をモニタリングするために様々な手法で解析されているが, 特に非線形時系列解析が有効である [2]. 本研究では, 非線形時系列解析手法の中でも特にリカレンスプロット [3](Recurrence Plot, 以下 RP) に着目した解析を行う. RP は, 力学系のアトラクタ上の 2 点間距離を用いて, 時系列データの非定常性検出や非線形力学系の特徴を解析可能なツールである. また, 再帰定量化解析 [4](Recurrence Quantification Analysis, 以下 RQA) を行うことで RP から非線形力学系の特徴を定量化することができる. 一般的には, RQA を用いる際の RP のサイズを大きくすることで, 非線形力学系の特徴量を高精度に定量化することができる. 逆に, 時系列長が短い場合, 非線形力学系の特徴量を正確に得ることは困難となる. 一方, 短い PPG データから生体システムの特徴を抽出可能となれば, 健康状態のモニタリングを高速化することが可能になる.

そこで本論文では, PPG データから生体システムの非線形力学系としての特徴量を正確に得るための必要最小限のデータ長を明らかにすることを目的とする. そのため, 本論文では PPG データから計算される RQA の指標が十分長い時系列長で計算した値と同程度となる最小のデータ長について調査する. 具体的には, RQA 指標を PPG データのデータ長を変化させて算出し, 十分長い時系列長を用いて計算した RQA 指標に対する誤差率が同程度となる時系列長を求めた. なお, 本論文では, 東京理科大学の学生のうち, 21~26 歳の健康な男女 11 名に行われた計測によって得られた PPG データを使用した. 以下では, PPG 時系列データを $P(t)$ とする.

2 解析手法

2.1 遅延座標系を用いた状態空間の再構成

現実世界のシステムでは全ての状態変数が観測されることは稀である. PPG データも, 心血管系のダイナミカルシステムから観測された 1 次元の時系列データである. このような場合, 観測時系列を時間遅延座標系へ変換することで, 背後にある非線形力学系のダイナミクスを再構成できる [6]. 具体的には観測時系列を x_t ($1 \leq t \leq n$) としたとき, 遅延ベクトル $\mathbf{X}_t = (x_t, x_{t+\tau}, x_{t+2\tau}, \dots, x_{t+(m-1)\tau})$ を用いて力学系を再構成する. ここで, m は再構成次元, τ は時間遅れである. 再構成次元 $m = 4$, 時間遅れ $\tau = 20$ [2] と設定することで, ある被験者の PPG データ $P(t)$ から再構成したアトラクタの例を図 1 に示す. 図 1 から, ねじれ構造を含んだ円環状のアトラクタ構造が確認できる.

2.2 リカレンスプロットと再帰定量化解析

RP [2] は, 力学系のアトラクタ上の 2 点間距離を用いて, 力学系のダイナミクスを, 二次元の 2 値画像として可視化する手法である. プロットパターンによって定性的に力学系の情報を得ることができる. RP の作成手順を以下に示す.

1. アトラクタ上の 2 点 $\mathbf{X}_i, \mathbf{X}_j$ 間のユークリッド距離 $D(i, j) = |\mathbf{X}_i - \mathbf{X}_j|$ を求める.
2. 二次元画像の第 (i, j) 画素の値 $RP_{i,j}$ を式 (1) で定義する.

$$R_{i,j} = \begin{cases} 1 & (D(i,j) \leq \theta) \\ 0 & (\text{otherwise}) \end{cases} \quad (1)$$

ここで、 θ は閾値である．本論文では、閾値 θ をアトラクタ上の 2 点間距離の最大値を $D_{\max}$ とし、 $\theta = 0.1D_{\max}$ と設定した．

PPG データから生成した RP の例を図 2 に示す．

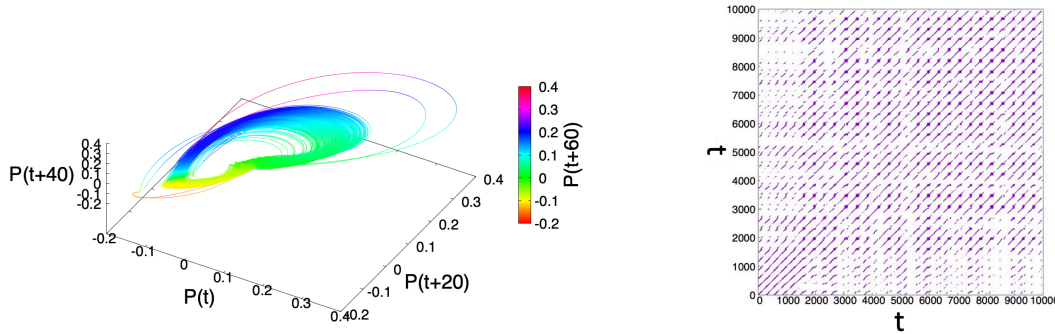


図 1: PPG データ $P(t)$ の再構成アトラクタの例 図 2: PPG データ $P(t)$ から生成した RP の例

再帰定量化解析 (Recurrence Quantification Analysis, RQA)[3] は RP のプロットパターンを定量化し、力学系の特徴を定量的に解析する手法である．RQA の値から力学系の決定論性や複雑性などを評価することができる．例えば、Determinism (以下、DET) は RP の決定論性を評価する統計量の一つである．DET の値 D は RP 内の全プロット数に対する原点からの対角線に平行な斜め線を構成するプロット数の割合で定義される (式 (2))．ここで、RP に含まれる長さが l の斜め線の本数を $P(l) = \sum_{i=1}^{N-l+1} \sum_{j=i+1}^{N-l+1} (1 - R_{i-1,j-1})(1 - R_{i+l,j+l}) \prod_{k=0}^{l-1} R_{i+k,j+k}$ とする．式 (2) の $l_{\min}$ は斜め線の最小の長さである．本論文では、 $l_{\min} = 2$ とした．

RP の斜め線の長さ l は、軌道が再帰した際に長さ l の間だけ接近しているため、長さ l の間は線形近似できる．よって、RP の斜め線の長さの平均値 L_{av} は短期予測可能な軌道の長さの平均として考えられる． L_{av} を式 (3) で定義する．

$$D = \frac{\sum_{l=l_{\min}}^{N-1} lP(l)}{\sum_{l=1}^{N-1} lP(l)} \quad (2) \quad L_{av} = \frac{\sum_{l=l_{\min}}^{N-1} lP(l)}{\sum_{l=l_{\min}}^{N-1} P(l)} \quad (3)$$

また、時系列の複雑さを評価する統計量の一つとして、斜め線の長さの確率分布 $P(l)$ のエントロピー E を求めることができる．RP 内の斜め線の長さが l である確率は $q(l) = P(l) / (\sum_{l=l_{\min}}^{N-1} P(l))$ で定義できる． E を式 (4) で定義する．

$$E = - \sum_{l=l_{\min}}^{N-1} q(l) \ln q(l) \quad (4)$$

軌道の停留の度合いを評価する統計量の一つである Laminarity は RP 内の全プロット数に対する垂直線を構成するプロット数の割合で求められる。RP に含まれる長さが v の垂直線の本数を $P(v) = \sum_{i=1}^{N-v+1} \sum_{j=i+1}^{N-v+1} (1 - R_{i,j-1})(1 - R_{i,j+v}) \prod_{k=0}^{v-1} R_{i,j+k}$ とし、Laminarity の値 L を式 (5) で定義する。

$$L = \frac{\sum_{v=v_{\min}}^N vP(v)}{\sum_{v=1}^N vP(v)} \quad (5)$$

ここで、 $v_{\min}$ は垂直線の最小の長さである。本論文では、 $v_{\min} = 2$ とした。データ長 100,000 の PPG データから再構成したアトラクタに対して、 D, L_{av}, E, L を計算した。その際、データ長 N のときの D, L_{av}, E, L の値に対する誤差率で評価した。

まず、数理モデルで時系列長を変えたときの誤差率の変化を調査する。決定論的カオスに従う数理モデルのレスラー方程式は $dx/dt = -y - z, dy/dt = x + ay, dz/dt = b + xz - cz$ で定義される [7]。パラメータは $a = 0.398, b = 2, c = 4$ とした。レスラー方程式のデータ長 N を変化させた際の各 RQA 指標の誤差率の変化を図 3 に示す。図 3 から、 D と L の誤差率は N によらず 0% であり、 L_{av}, E の誤差率は RP のサイズが大きくなるにつれ、変動が小さくなり、値は 0 に近づいている。これらの結果は特徴量を高精度に定量化できることを示すものである。

3 解析結果

計測した PPG データをデータ長 $N = 1,000$ から 100,000 まで 1,000 刻みに変化させ、再構成次元 $m = 4$ 、時間遅れ $\tau = 20$ とした再構成アトラクタからリカレンスプロットを作成し、各 RQA を算出する。このときの誤差率の平均の推移を図 4 に示す。誤差率の平均は赤線で示し、誤差率が 1% 未満になったデータ長を赤い破線で示した。

図 4 (a), (d) を見ると、 D と L の誤差率は N によらず 0.2% 以下である。これは、PPG データの D と L は短いデータ長でも推定可能であることを示すものである。一方、図 4 (b), (c) から E と L_{av} はデータ長が短いほど誤差が大きくなる傾向にある。誤差率が 1% 未満となるデータ長は E が 50,000、 L_{av} が 90,000 であり、 D, L に比べて長いデータが必要であることがわかった。よって、調べる RQA 指標に合わせて時系列長を設定することで必要なデータ数を削減できることがわかった。

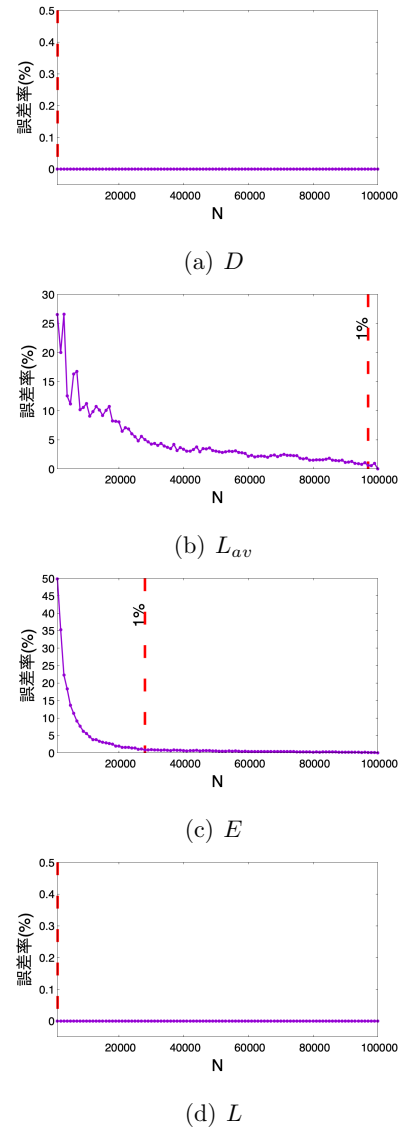


図 3: レスラー方程式の RQA 指標の誤差率の変化

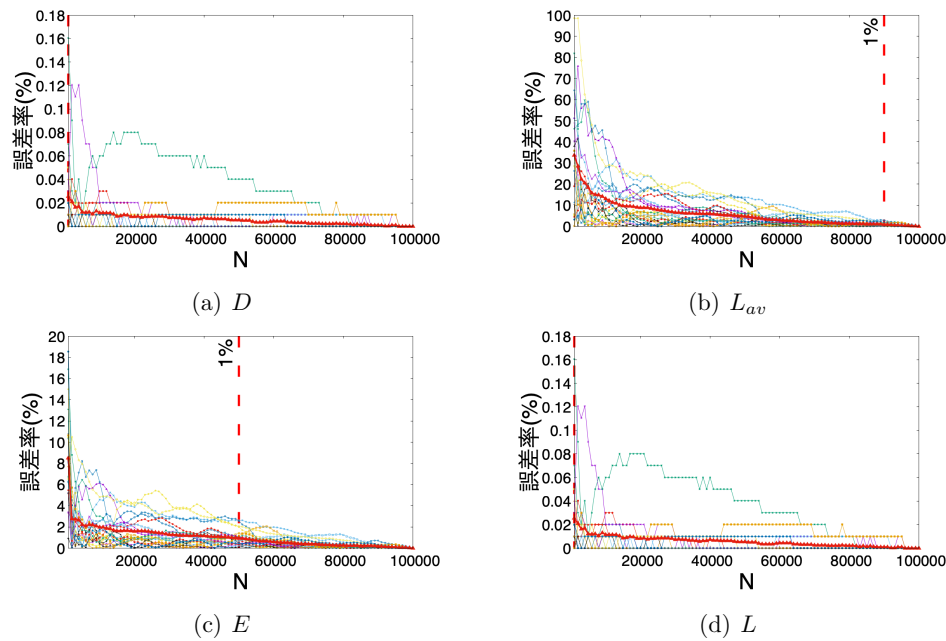


図 4: データ長 N を変化させた際の RQA 指標の変化と平均値の変化

4 まとめ

本論文では、複数の被験者の PPG データから算出した RQA 指標 (D , L_{av} , E , L) が、十分長い時系列長で計算した値と同等の結果となる最小のデータ長を調査した。具体的にはまず、PPG データから再構成アトラクタを作成し、その RP を作成後、データ長 N を変化させて RQA 指標を算出した。次に、データ長 100,000 に対する RQA 指標の誤差率を算出した。その結果、 D と L はデータ長 1,000 からデータ長 100,000 までの結果にほとんど差は見られず、この二つの指標を調べる場合にはデータ長は 1,000 で十分であることがわかった。一方、 E と L_{av} はデータ長が短いとき、データ長 100,000 に比べて大きな誤差率が見られ、誤差率が 1% 未満となるためには、 E は 50,000、 L_{av} は 90,000 のデータ長が必要であることがわかった。

参考文献

- [1] J. Allen, “Photoplethysmography and its application in clinical physiological measurement,” *Physiological Measurement*, Vol. 28, No. 3, pp. 1–39, 2007.
- [2] N. Sviridova and K. Sakai, “Human photoplethysmogram: new insight into chaotic characteristics,” *Chaos, Solitons & Fractals*, Vol. 77, pp. 53–63, 2015.
- [3] J.-P. Eckmann *et al.*, “Recurrence Plots of Dynamical Systems,” *Europhysics Letters*, Vol. 4, No. 9, pp. 937–977, 1987.
- [4] N. Marwan *et al.*, “Recurrence plots for the analysis of complex systems,” *Physics Reports*, Vol. 438, No. 5, pp. 237–239, 2007.
- [5] 東京デバイス株式会社, <https://tokyodevices.com/items/188>, (令和 4 年 2 月 1 日閲覧).
- [6] F. Takens *et al.*, *In Detecting strange attractors in turbulence*, Dynamical systems and turbulence, Lecture Notes in Mathematics, Vol. 898, pp. 366–381, 1981.
- [7] Otto E. Rössler, “An equation for continuous chaos,” *Physics Letters A*, Vol. 57, No. 5, pp. 397–398, 1976.

言語共起ネットワークのモチーフ解析

石川竜吉 (池口徹 教授, Nina Sviridova 助教)

1 はじめに

インターネットなどの発展に伴い、あらゆる国や地域から様々な情報を容易に入手できるようになっている。多くの場合、異なる国や地域から得られる情報には固有の言語が用いられている。即ち、これらのデータを効率的に解析するためには、異なる言語情報に対して汎用的に利用できる解析手法が不可欠である。そのための手法の一つとして、文章構造を複雑ネットワークと捉え、数理的な解析を行う共起ネットワークを用いた手法が提案されている [1-3]。共起ネットワークとは、文章内で連続して出現した単語同士を繋いで作成したネットワークである。例えば、ネットワーク中のクラスタ構造を用いることで言語ネットワークの局所構造が明らかにされている [2]。また、文献 [3] では、クラスタ係数、平均頂点間距離などの複雑ネットワークの大域的な特徴量を用いて共起ネットワークの調査を行っている。本研究では、ネットワークモチーフと呼ばれるネットワークの局所構造を定量化する手法を用いて言語の共起ネットワークを解析する。

ネットワークモチーフとは、複雑な形状を有する小規模なサブグラフのうち、特にネットワークの中に有意に多く出現する構造である。本論文では、同じ内容が多くの言語に翻訳されている、新約聖書を対象としてモチーフ解析を行い、ネットワークの局所構造という観点から文章構造を調査した。その結果、全ての言語において単語同士の接続を媒介する頂点が存在すること、また、その役割が特定の品詞に集中していることがわかった。

2 実験手法

共起ネットワークとは、文章中の単語を頂点とし、連続して出現する単語同士を接続するという方法で作成されるネットワークである。本論文では、元となる文章を構成する単語を形態素解析により原形に変換する。その際、品詞情報も付与することで共起ネットワークの頂点とした。また、接続される単語の数 (共起数) $m=1, 2$ とした。共起ネットワークの作成手順を図 1 に示す。

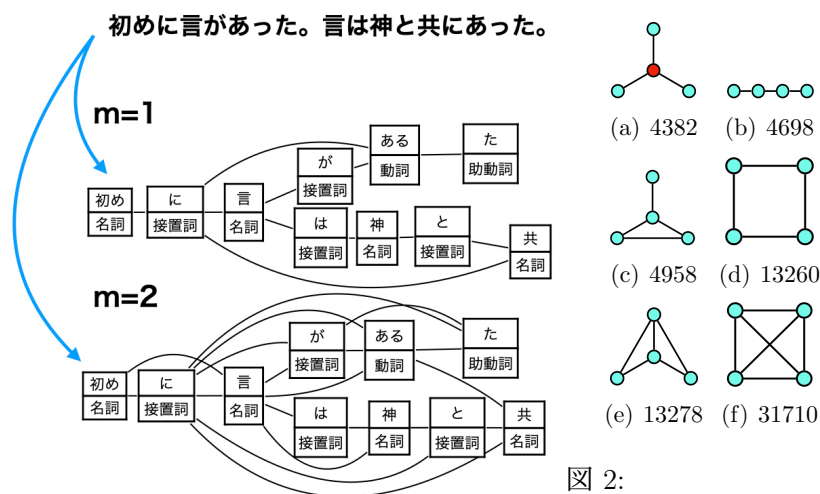


図 1: 共起ネットワークの作成手法

図 2:
無向ネットワークにおける
4 頂点サブグラフ

本論文では、4 頂点のサブグラフについて調査した。無向ネットワークでの 4 頂点サブグラフは、図 2 に示した 6 種類である。サブグラフの頂点はその構造から複数に分類することができる。例えば、ID4382 のサブグラフは、図 2 (a) のように、全ての枝が集まる中心頂点 (赤色) と、これに接続する周辺頂点に分けることができる。

あるネットワーク G におけるサブグラフ H の出現回数を H の頻度 $f_G(H)$ とし [5], H の頻度を全てのサブグラフの頻度の合計で割っ

たものをサブグラフ H の濃度 $C_G(H) = f_G(H) / \sum_{I \in S} f_G(I)$ とする [5]。ここで、 S はネットワーク G に出現したサブグラフ全体の集合である。

本論文では、言語ごとに、サブグラフの濃度 $C_G(H)$ を求め、サブグラフの有意性を調査した。こ

で、サブグラフの有意性は、ネットワーク G におけるサブグラフ H の頻度 $f_G(H)$ または濃度 $C_G(H)$ に対して、 G をランダム化したネットワーク R の頻度 $f_R(H)$ または濃度 $C_R(H)$ が同じとなるか、上回った割合 ($p_f(H) = n_f(H)/N$, $p_C(H) = n_C(H)/N$) を用いた [5]. ただし、ランダム化回数が N , $f_G(H) \leq f_R(H)$ となる回数が $n_f(H)$, $C_G(H) \leq C_R(H)$ となる回数が $n_C(H)$ である. $p_f(H) < 0.01$ であるサブグラフを有意とする [4]. また, $p_f(H) \geq 0.01$ であったが $p_C(H) < 0.01$ であるものも存在したため, そちらについても記録した. なお, 頻度, 濃度, p 値の計算には, NetMODE [5] を使用した.

3 結果

本論文では, 文献 [3] で使用されている, 新約聖書のうちヨハネ伝, マルコ伝, マタイ伝, ルカ伝の4種類の福音書について, 8言語, 13種類のデータから作成した共起ネットワークを用いた (表1).

3.1 サブグラフの濃度, 有意性の調査

表1: 言語と訳バージョン

語族	言語	訳バージョン数
シナ・チベット語族	中国語	1
ウラル語族	フィンランド語	2
日本語族	日本語	2
インド・ヨーロッパ語族	英語	2
	フランス語	2
	ドイツ語	1
	ギリシャ語	2
	ロシア語	1

ヨハネ伝に対する濃度を図3に示す. なお, 濃度, 有意性については, ヨハネ伝以外の福音書についても同様の結果であった. 図3より, ID4382のサブグラフ (図2 (a)) が最も高いことが分かる. 次に, サブグラフの有意性を表2に示す. 表2では, $p_f(H) < 0.01$ となったものを $\circ$, $p_C(H) < 0.01$ のみ満たしたものを Δ , どちらも満たさなかったものを $\times$ とした.

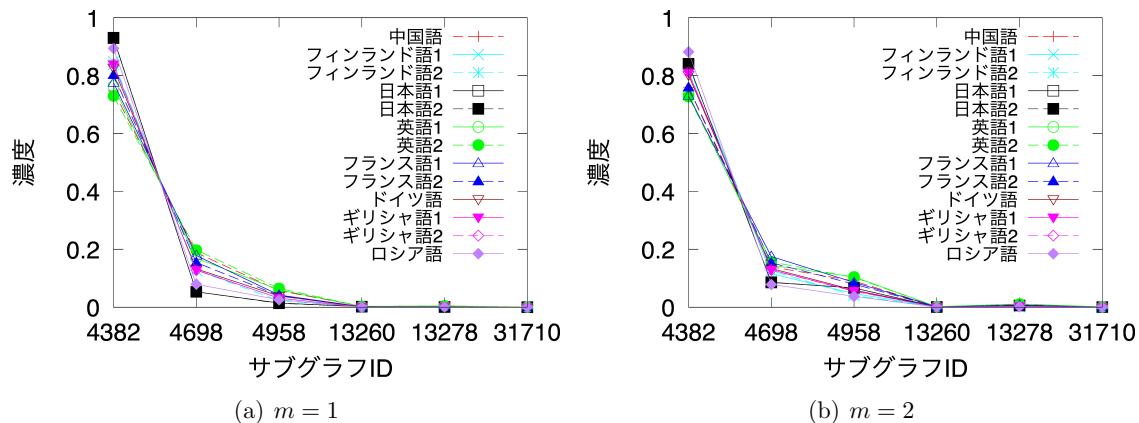


図3: ヨハネ伝におけるサブグラフの濃度
表2: ヨハネ伝におけるサブグラフの有意性

(a) $m = 1$

言語	4382	4698	4958	13260	13278	31710
中国語	$\circ$	$\times$	$\times$	$\circ$	$\times$	$\times$
英語1	$\circ$	$\circ$	$\times$	$\circ$	$\times$	$\times$
英語2	$\circ$	$\circ$	$\times$	$\circ$	$\times$	$\times$
フィンランド語1	$\circ$	$\times$	$\times$	$\circ$	$\times$	$\times$
フィンランド語2	$\circ$	$\times$	$\times$	$\circ$	$\times$	$\times$
フランス語1	$\circ$	$\times$	$\times$	$\circ$	$\times$	$\times$
フランス語2	$\circ$	$\times$	$\times$	$\circ$	$\times$	$\times$
ドイツ語	Δ	$\times$	$\times$	$\times$	$\times$	$\times$
ギリシャ語1	$\circ$	$\times$	$\times$	$\times$	$\times$	$\times$
ギリシャ語2	$\circ$	$\times$	$\times$	$\times$	$\times$	$\times$
日本語1	$\circ$	$\times$	$\times$	$\circ$	$\times$	$\times$
日本語2	$\circ$	$\times$	$\times$	$\circ$	$\times$	$\times$
ロシア語	Δ	$\times$	$\times$	$\times$	$\times$	$\times$

(b) $m = 2$

言語	4382	4698	4958	13260	13278	31710
中国語	$\times$	$\times$	$\circ$	$\times$	$\circ$	$\circ$
英語1	$\times$	$\times$	$\circ$	$\times$	Δ	$\times$
英語2	Δ	$\times$	$\times$	$\times$	$\times$	$\times$
フィンランド語1	Δ	$\times$	$\circ$	$\times$	$\times$	$\times$
フィンランド語2	Δ	$\times$	Δ	$\times$	$\times$	$\times$
フランス語1	Δ	$\times$	$\times$	$\times$	$\times$	$\times$
フランス語2	Δ	$\times$	$\times$	$\times$	$\times$	$\times$
ドイツ語	Δ	$\times$	$\circ$	$\times$	Δ	$\times$
ギリシャ語1	Δ	$\times$	$\circ$	$\times$	$\times$	$\times$
ギリシャ語2	Δ	$\times$	$\circ$	$\times$	$\times$	$\times$
日本語1	Δ	$\times$	$\circ$	$\times$	$\times$	$\times$
日本語2	Δ	$\times$	$\circ$	$\times$	$\times$	$\times$
ロシア語	Δ	$\times$	$\circ$	$\times$	$\circ$	$\circ$

表2より, $m = 1$ では, ほとんどの言語で ID4382 のサブグラフが有意であることが分かる. また, 比較的多くの言語で ID13260 のサブグラフが有意となっている. 図3, 表2の結果から, $m = 1$

の場合は、濃度が最も高く、ほとんどの言語で有意となった ID4382 のサブグラフが重要であると考えられる。また、 $m = 2$ の場合は、ID4382, ID13260 のサブグラフは全ての言語で有意ではない。また、 $m = 1$ では有意ではなかった ID4958 のサブグラフが複数の言語において有意となっていた。

3.2 サブグラフを構成する品詞の調査

前節の実験では、ネットワーク構造においてどのサブグラフが有意に出現するのかを調査した。しかし、頂点の品詞を考慮していないため、サブグラフの文法的な役割の解析を行うことはできない。そこで本節では、 $m = 1$ のネットワークに対して、全ての言語で濃度が高く、ほとんどの言語において有意となった ID4382 のサブグラフに注目し、その文法的な役割を解析するため、ID4382 のサブグラフを構成する頂点の品詞を調査した。調査にあたり、ID4382 のサブグラフを構成する品詞のうち、図 2 (a) の、3つの頂点が集まる中心頂点 (赤色) を対象とした。まず、各文書において特に ID4382 のサブグラフの中心頂点となりやすい品詞を調査した。調査は、ID4382 のサブグラフの中心頂点となった回数を品詞ごとに足し合わせ、品詞ごとの頂点数で割ることで平均して行った。結果を図 4 に示す。ただし、それぞれの平均回数を、言語ごとに最大値で割ることで、最大値が 1 となるように正規化して示している。図 4 を見ると、ヨハネ伝の中国語では、接置詞で最大値を取っているため数値が 1 となっており、代名詞が該当した回数は接置詞での数値の 0.3 倍程度である。また、ヨハネ伝の英語の一つ目の訳バージョンでは、接続詞で最大値をとり、限定詞がその 0.4 倍程度である。

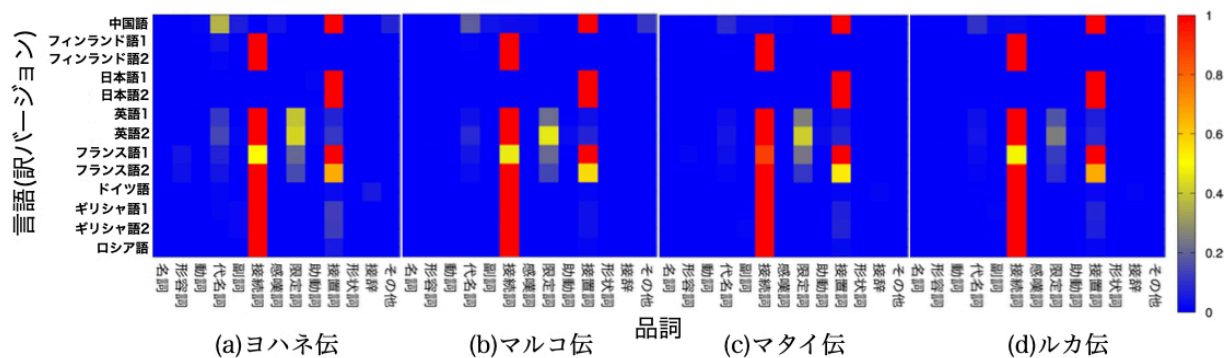


図 4: ID4382 の中心頂点における品詞の頻度

図 4 を見ると、ID4382 のサブグラフの中心頂点となりやすい品詞は、言語ごとに、接続詞、接置詞に大きく分けられる。ただし、フランス語では、同じ言語でも、訳バージョンによって異なる結果となった。そこで、中心頂点となった回数が特に集中していた接続詞、接置詞についての値を取り出した。結果を図 5 に示す。ただし、ID4382 のサブグラフの中心頂点となった回数の平均を品詞全体の合計値で割ることで正規化している。図 5 より、本論文で対象とした 8 言語は、ID4382 のサブグラフの中心頂点となりやすい品詞によって、接置詞に集中している中国語と日本語、接続詞に集中しているフィンランド語、英語、ドイツ語、ギリシャ語、ロシア語、どちらも高い割合で中心頂点となっているフランス語の 3 種類に分かれることが分かる。

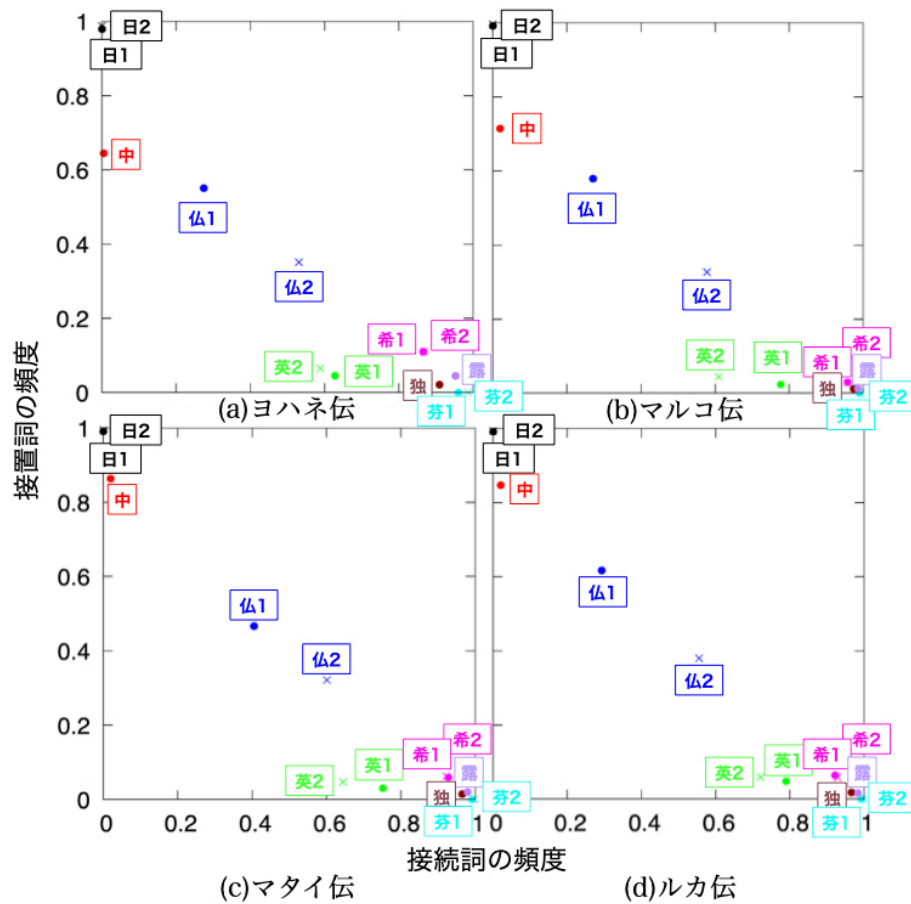


図 5: 接続詞, 接置詞が ID4382 のサブグラフの中心頂点となった平均頻度の関係

4 まとめ

本論文では, 新約聖書のテキストから作成した共起ネットワークに対してモチーフ解析を行うことで, 言語間の違いを調査した. その結果, 異なる言語間でも局所構造には共通点があること, さらには, その品詞構成にも複数言語間で共通点があることが示唆された. 今後の課題として, 有向グラフとする, 共起数を増やすなどの拡張が必要である. また, 聖書以外の文書を対象とすることにより, さらに詳細な調査を行うことが必要である.

参考文献

- [1] R. Cancho and R. Sole, “The Small World of Human Language,” *Proceedings of the Royal Society B-Biological Sciences*, Vol. 268, No. 1482, pp. 2261–2265, 2001.
- [2] Y. Shimada, M. Tatara, K. Fujiwara, and T. Ikeguchi, “Formation Mechanisms of Local Structures in Language Networks,” *Europhysics Letters*, Vol. 127, No. 5, 2019.
- [3] K. Magishi, T. Matsumoto, Y. Shimada, and T. Ikeguchi, “Investigation of the Structural Features of Word Co-occurrence Networks with Increasing Numbers of Connected Words,” to appear in *NOLTA, IEICE*, 2022.
- [4] R. Milo, S. Shen-Orr, S. Itzkovitz, N. Kashtan, D. Chklovskii, and U. Alon, “Network Motifs: Simple Building Blocks of Complex Networks,” *Science*, Vol. 298, No. 5594, pp. 824–827, 2002.
- [5] X. Li, D. S. Stones, H. Wang, H. Deng, X. Liu, and G. Wang, “NetMODE: Network Motif Detection without Nauty,” *PLOS ONE*, Vol. 71, No. 12, e50093, 2012.

バイクシェアリングシステム利用情報の テンポラルネットワーク解析

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1 はじめに

バイクシェアリングシステム (BSS) とは、利用者が、特定の地域に配置されているステーション間を自転車で行き来することのできる公共交通システムである。BSS の開発により、自転車を用いた短距離の移動によるラストワンマイル問題の解決、温室効果ガスの削減が期待されている [1]。

BSS では自転車が一方通行ばかりに利用されると、自転車を借りることができないステーション、返却できないステーションが発生する。この問題を解決するため、実際の BSS では、自転車回収車を用いた再配置作業が行われている。また、この再配置作業を効率的に行うための自転車回収車の巡回路を求める研究も行われている [2, 3, 4]。

一方、近年の IoT 技術の発展に伴い、実際の BSS のステーション情報や利用履歴データが公開されている。例えば、バルセロナで実施されている BSS[5] の実データを使用し、予測対象の周囲のステーションの時系列データを学習する ARMA モデルを用いた予測法が提案されている [6]。また、バルセロナの BSS のデータを使用して、クラスター分析を用いた複数の予測モデルの比較が行われている [7]。さらに、ボストン [9]、ワシントン D.C.[10]、ニューヨーク [11]、シカゴ [12] の BSS を対象として、自転車の貸し出しと返却をイベントの発生とする点過程の側面からの解析が行われている [13, 14, 15]。これらに加えて、公開されている BSS データを用いて予測精度を競うコンテスト [8] も開催されており、効率的な BSS の運用が現在の課題となっている。

これまでの実データ解析 [6, 7, 13, 14, 15] では、あるステーションで貸し出された自転車がどのステーションに返却されたのかという情報を考慮していない。そこで本論文では、まず、サンフランシスコの BSS の実際の利用履歴データ [16] を対象として、顧客の属性、利用時間帯などで分け、各ステーションに対する自転車の利用間隔の統計的な解析を行う。次に、ステーション間の自転車の移動を重み付き有向ネットワークと捉え、この有向ネットワークが時間の経過と共に変化するテンポラルネットワークの状態遷移ダイナミクスを明らかにする。

2 BSS の利用情報に対する統計的な時系列解析

本研究では、まず、統計的な観点からの解析を行うことで、BSS の時系列データの基礎的な特徴を明らかにする。文献 [14] では、ワシントン D.C. の BSS について、自転車が貸し出された時間をイベントの発生としたラスタプロットを作成し、季節的な変化を調査している。

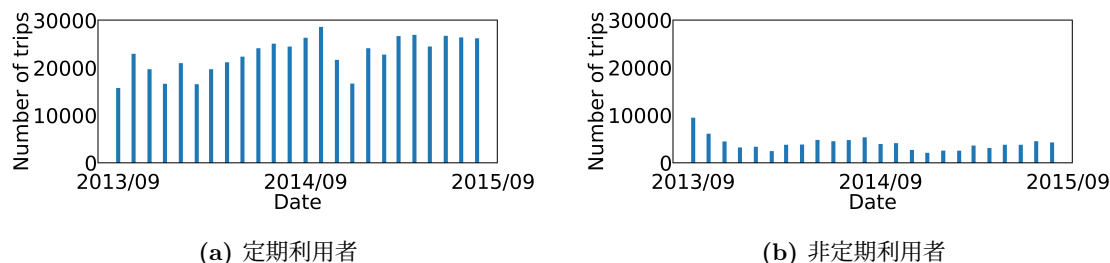


図 1: 2013 年 9 月から 2015 年 8 月までの 2 年間にわたる、(a) 定期利用者と (b) 非定期利用者の貸し出し数の棒グラフ。

本論文では、サンフランシスコにおける、San Francisco Bay Area Bike Share の、2013 年 9 月から 2015 年 8 月までの利用履歴データ [16] を用いた。データには、70 個のステーション、647,025 個

の自転車の移動履歴が記録されている．図1は，2013年9月から2015年8月までにおける，月毎の定期利用者と非定期利用者の自転車の貸し出し数の変化である．横軸が日付で，縦軸が月毎の貸し出し数である．定期利用者の貸し出し数は，2013年9月から2014年8月までの1年間の方が，2014年9月から2015年8月の1年間よりも少ないことが分かる．しかし，非定期利用者の貸し出し数は，2013年9月から2014年8月までの1年間の方が，2014年9月から2015年8月の1年間よりも多いことが分かる．これは，非定期利用者が定期利用者になったことが理由であると考えられる．

図2(a)，(b)は，自転車の利用数が多い，2013年10月8日の，定期利用者と非定期利用者の貸し出し数である．横軸が時間（分），縦軸が貸し出し数を表す．図2(c)，(d)は，2013年10月8日の，定期利用者と非定期利用者のラスタプロットであり，どのステーションがいつ貸し出されたかを表す．横軸が時間（分），縦軸がステーションIDである．図2より，定期利用者の貸し出し数は，朝夕の通勤時間帯で多くなっていることが分かる．一方，非定期利用者の貸し出し数の時間変化には特徴がないことが分かる．

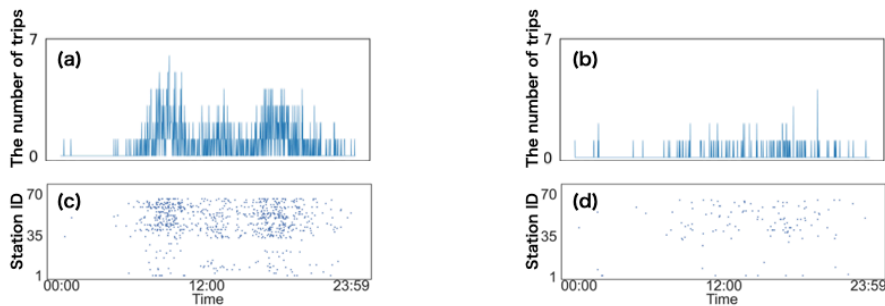


図 2: 2013 年 10 月 8 日の定期利用者と非定期利用者の利用数とラスタプロット

次に，自転車の貸し出しと返却のタイミングのパターンの統計的特性について調査するために変動係数 (C_V)，局所変動係数 (L_V) を使用する [17]． i 番目のイベントが発生した時間を t_i ， $i+1$ 番目のイベントが発生した時間を t_{i+1} とし， i 番目の inter-event intervals (IEI) を $T_i = t_{i+1} - t_i$ とする．IEI を用いて， C_V は， $C_V = \sqrt{1/(n-1) \sum_{i=1}^n (T_i - \bar{T})^2 / \bar{T}}$ と表される．ただし， $\bar{T} = 1/n \sum_{i=1}^n T_i$ である． C_V は貸し出し間隔の全体的な変動を表し， $C_V = 0$ のとき，イベントは規則的に発生していることを示す． $C_V = 1$ のとき，イベントの発生はポアソン過程に従うことを示す．図3(a)～図3(c)は，日中と夜間，平日と週末，定期利用者と非定期利用者に分けて算出した，2年分のステーション毎の貸し出しの C_V のヒストグラムである．日中と夜間，定期利用者と非定期利用者の間には有意差が無いが，平日と週末の間には有意差があることが分かった．しかし，図2から，定期利用の有無に関わらず，日中の自転車の利用は多く，夜間の利用は少ないことが分かる．そこで，次に全体のイベントの発生率に変動がある場合でも局所的な IEI の特性を抽出できる L_V を使用する．

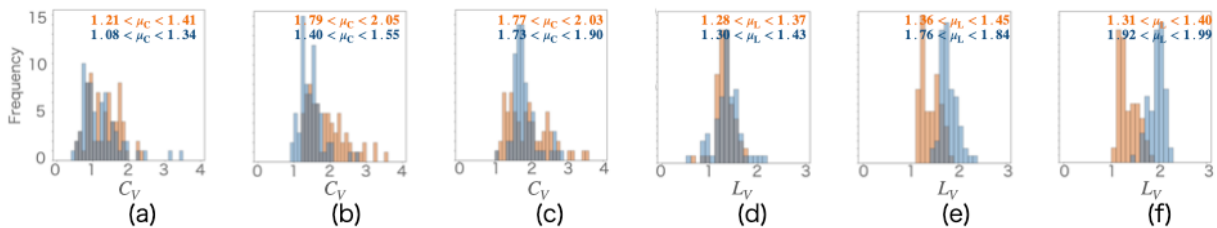


図 3: 時間，属性別の C_V ， L_V のヒストグラム．横軸が C_V ， L_V ，縦軸が度数． C_V の 95% 信頼区間を μ_C の範囲， L_V の 95% 信頼区間を μ_L の範囲で示した．(a) 日中（オレンジ）と夜間（青）の C_V ．(b) 平日（オレンジ）と週末（青）の C_V ．(c) 定期利用者（オレンジ）と非定期利用者（青）の C_V ．(d) 日中（オレンジ）と夜間（青）の L_V ．(e) 平日（オレンジ）と週末（青）の L_V ．(f) 定期利用者（オレンジ）と非定期利用者（青）の L_V ．

IEI を用いて、局所変動係数 (L_V) は、 $L_V = 1/(n-1) \sum_{i=1}^{n-1} 3(T_i - T_{i+1})^2 / (T_i + T_{i+1})^2$ と表される。 L_V は局所的な変動を表し、 $L_V = 0$ のとき、イベントは規則的に発生していることを示す。 $L_V = 1$ のとき、イベントの発生はポアソン過程に従うことを示す。 図 3(d)~図 3(f) は、日中と夜間、平日と週末、定期利用者と非定期利用者に分けて算出した、2 年分のステーション毎の貸し出しの L_V のヒストグラムである。 日中と夜間には有意差が無いが、平日と週末、定期利用者と非定期利用者の間には有意差があることが分かった。

3 BSS に対する複雑ネットワーク理論の観点からの解析

統計的な時系列解析の観点からでは、自転車が貸し出されたタイミング、返却されたタイミングのみを考慮しているため、あるステーションで借りられた自転車がどこに返却されるかについての考察は困難である。そこで、自転車が貸し出されたステーションを始点、返却されたステーションを終点とする有向重み付きネットワークとした解析を行う。ステーションと自転車の移動を有向重み付きネットワークにする際に、70 行 70 列の隣接行列を作成した。各行、各列はステーション ID に対応しており、期間中のある日付 i において、ステーション k からステーション l に自転車の移動が N 回あったとき、要素 $A_{k,l}^i = N$ とする行列 A^i を隣接行列とする。任意の 2 日における隣接行列の距離 $d_{i,j}$ は $d_{i,j} = \sum_{k=1}^{70} \sum_{l=1}^{70} (A_{k,l}^i - A_{k,l}^j)^2$ と表される。任意の 2 日における距離 $d_{i,j}$ を、全ての組み合わせに対して求めて行列で表したものが距離行列 D である。距離行列 D の要素の最小値 $\min_{i \neq j} d_{i,j}$ と最大値 $\max_{i \neq j} d_{i,j}$ に対して、閾値 $\theta = \min_{i \neq j} d_{i,j} + 0.1(\max_{i \neq j} d_{i,j} - \min_{i \neq j} d_{i,j})$ を設定し、2 値距離行列のリカレンスプロット $RP_{i,j} = 0(d_{i,j} \geq \theta), 1(d_{i,j} < \theta)$ を定義する [18]。

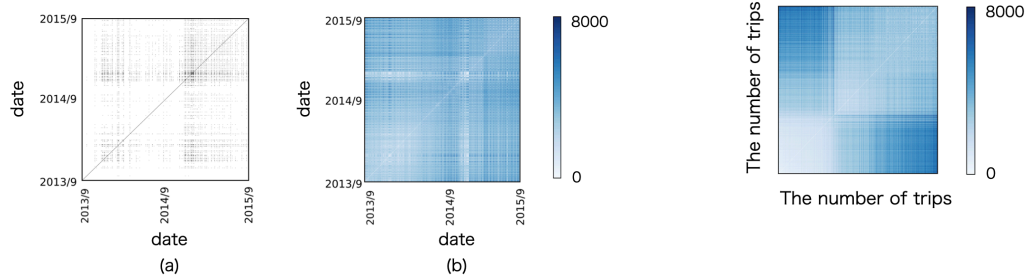


図 4: (a) 2 値距離行列 RP を可視化した図。 (b) 距離行列 D のカラーマップ。

図 5: 図 4(b) の軸を、自転車の利用数で昇順に並べ替えたカラーマップ。

図 4(a) の黒い部分より、冬季の隣接行列は、どの季節の隣接行列に対しても距離が小さくなっていることが分かる。冬季の自転車の利用数は少ないので、自転車の利用数と隣接行列同士間の距離の関係をみるために、図 4(b) の軸を、自転車の利用数で昇順に並び替えたカラーマップを図 5 に示した。図 5 より、利用数が小さい日同士の隣接行列の距離（左下）は、利用数が大きい日同士の隣接行列の距離（右上）よりも小さくなっていることが分かる。また、利用数が小さい日と利用数が大きい日の隣接行列の距離（左上、右下）は、利用数が小さい日同士の隣接行列の距離（左下）と利用数が大きい日同士の隣接行列の距離（右上）よりも大きくなっていることが分かる。

4 まとめ

本論文では、2013 年 9 月から 2015 年 8 月までの、サンフランシスコにおける BSS の利用履歴データに対して、ステーション間の自転車の移動を重み付き有向ネットワークとし、テンポラルネットワークの状態遷移ダイナミクスを複雑ネットワーク理論の観点から解析を行なった。まず、統計的な時系列解析を行なった結果、時間別、利用者の属性別で、利用パターンに差があることが分かった。次に、ネットワーク解析を行なった結果、ネットワークの時間変化において、冬季の隣接行列は、どの季節の隣接行列に対しても小さい距離を持ち、さらに、BSS 全体の自転車の移動量が、ネットワークの時間変化に影響していることが分かった。このことは、BSS の自転車の移動を予測する際に、BSS 全体の自転車移動量の増減を考慮する必要があることを示唆している。今後は、サンフ

ランシスコのBSSだけでなく、様々な都市のBSSの特徴を調べ、各BSSにおいて、実際のシステムに適用できるような自転車再配置問題の作成を検討する必要がある。

参考文献

- [1] D. Paul, “Bike-sharing: History, impacts, models of provision, and future,” *Journal of public transportation*, Vol. 12, No. 4, pp. 41–56, 2009.
- [2] H. Tsushima, T. Matsuura and T. Ikeguchi, “Strategy for Exploring Feasible and Infeasible Solution Spaces to Solve a Multiple-Vehicle Bike Sharing System Routing Problem,” *Applied Sciences*, Vol. 11, No. 16, 7749, 2021.
- [3] S. Wada, T. Matsuura and K. Numata, “Heuristic Methods for the Bike-Sharing System Routing Problem,” *Journal of Signal Processing*, Vol. 17, No. 4, pp. 115–118, 2013.
- [4] D. Mauro, H. Eleni, I. Manuel and N. Stefano, “The bike sharing rebalancing problem: Mathematical formulations and benchmark instances,” *Omega*, Vol. 45, pp. 7–19, 2014.
- [5] Bike Sharing System bicing Official Site. <https://www.bicing.barcelona/> (最終閲覧日: 2022 年 1 月 4 日).
- [6] A. Kaltenbrunner, R. Meza, J. Grivolla, J. Codina and R. Banchs, “Urban cycles and mobility patterns: Exploring and predicting trends in a bicycle-based public transport system,” *Pervasive and Mobile Computing*, Vol. 6, No. 4, pp. 455–466, 2010.
- [7] J. Froehlich, J. Neumann and N. Oliver, “Sensing and predicting the pulse of the city through shared bicycling,” *Proc. of 2009 International Joint Conference on Artificial Intelligence*, pp. 1420–1426, 2009.
- [8] SIGNATE Student Cup 2021 秋. オペレーション最適化に向けたシェアサイクルの予測, <https://signate.jp/competitions/549/> (最終閲覧日: 2022 年 1 月 15 日).
- [9] Bike Sharing System BLUEbikes Official Site, <https://www.bluebikes.com/> (最終閲覧日: 2022 年 1 月 14 日).
- [10] Bike Sharing System capital bikeshare Official Site, <https://www.capitalbikeshare.com/> (最終閲覧日: 2022 年 1 月 14 日).
- [11] Bike Sharing System citi bike Official Site, <https://account.citibikenyc.com/access-plans/> (最終閲覧日: 2022 年 1 月 14 日).
- [12] Bike Sharing System Divvy bikes Official Site, <https://ride.divvybikes.com/about/> (最終閲覧日: 2022 年 1 月 14 日).
- [13] H. Tsushima and T. Ikeguchi, “Statistical analysis of usage history of bicycle sharing systems,” to appear in *NOLTA, IEICE*, 2021.
- [14] 對馬帆南, 池口徹, バイクシェアリングシステムの利用履歴の統計的な解析と季節的な影響, 電子情報通信学会技術研究報告, Vol. 121, No. 307, pp. 90–95, 2021.
- [15] 對馬帆南, 池口徹, ユーザ属性に着目したバイクシェアリングシステム利用履歴データの解析, 電子情報通信学会 2022 年総合大会, 2022 年 3 月発表予定.
- [16] SF Bay Area Bike Share Anonymized bike trip data from August 2013 to August 2015, <https://www.kaggle.com/benhamner/sf-bay-area-bike-share/> (最終閲覧日: 2022 年 1 月 2 日).
- [17] S. Shinomoto, K. Miura and S. Koyama, “A measure of local variation of inter-spike intervals,” *Biosystems*, Vol. 79, Nos. 1–3, pp. 67–72, 2005.
- [18] J.-P. Eckmann, S. Oliffson Kamphorst and D. Ruelle, “Recurrence plots of dynamical systems,” *Europhysics Letters*, Vol. 4, pp. 973–977, 1987.

Izhikevich ニューロンモデルの周期入力に対する応答の解析

塚本陽太 (池口徹 教授, Nina Sviridova 助教)

1 はじめに

人間の脳にはニューロンと呼ばれる細胞が1,000億個以上存在する。ニューロンは、他のニューロンと複雑に結合している。これらのニューロンからの入力に応じて電気信号を生成(以下、発火)し、伝達することで情報を処理している。即ち、ニューロンに外部入力を与えた際のダイナミクスを調査し、どのような応答を示すかを解析することは、脳内の情報処理原理の解明に必要である。

実際のニューロンの周期入力に対する応答の研究では、周期応答、準周期応答、カオス応答の発生が確認されている。例えば、イソアワモチの巨大ニューロンに正弦波を入力として印加すると、カオス応答が発生することが示されている[1]。また、正弦波で刺激されたイカの巨大軸索の応答は、周期応答、準周期応答、カオス応答となることも示されている[2]。

一方、ニューロンの数理モデルの周期入力に対する応答についても報告がされている。例えば、Hodgkin-Huxley モデル[3]に正弦波電流を印加すると、イカの巨大軸索と同様の応答が生じることが示されている[4]。また、Izhikevich ニューロンモデル[5]の周期入力に対する応答の調査では、正弦波の m 回のサイクル中に n 回発火する $n:m$ モードロックが生じることが示されている[6]。しかし、Izhikevich ニューロンモデルが、周期入力に対して準周期的あるいはカオス的な応答を示すかは明らかにされていない。

そこで本研究では、Izhikevich ニューロンモデルの周期入力に対する応答を3つの方法[P1, P2, P3]で調査した。まず、相平面上の解軌道がどのように振る舞うのかを調査した。次に、ISI (Interspike Interval) の多様度指数を用いて、応答の周期性を評価した。さらに、ストロボ観測点を用いて応答の種類を同定した。

2 ニューロンモデル

ニューロンの細胞膜の外側を基準とした、外側と内側の電位差を膜電位という。ニューロンは、入力を受けると膜電位が変動し、閾値以上になると発火する。このようなニューロンの活動を再現するために、さまざまな数理モデルが提案されている。本研究では、計算量が少なく、豊富な発火パターンを再現できる Izhikevich ニューロンモデル[5]を用いた。Izhikevich ニューロンモデルは、式(1), (2)で定義される。

$$\begin{cases} \dot{v} = 0.04v^2 + 5v + 140 - u + I(t), \\ \dot{u} = a(bv - u), \end{cases} \quad (1)$$

$$\text{if } v \geq 30, \text{ then } v \leftarrow c, u \leftarrow u + d. \quad (2)$$

ここで、 v は膜電位 [mV], u は回復変数, $I(t)$ は入力電流である。 $\dot{v}, \dot{u}$ は時間 t [ms] による微分である。なお、パラメータ a, b, c, d を適切に設定することで、様々な発火パターンを再現できる。本稿では、Regular Spiking (RS) と呼ばれる応答の結果を報告する。また、 $v \geq 30$ [mV] のとき、ニューロンが発火したとみなし、式(2)にもとづき v, u をリセットする。

本研究で使用した周期入力 $I(t)$ を式(3)に示す。ここで、式(3)は直流成分 I_{DC} と交流成分 I_{AC} からなる正弦波であり、 A は振幅、 T は周期である。

$$I(t) = I_{DC} + I_{AC} = I_{DC} + A \sin \frac{2\pi}{T} t. \quad (3)$$

3 解析手法

3.1 相平面

相平面は微分方程式の各変数を軸にとった直交座標系のことであり、解の挙動を定性的に調べることができる。また、相平面上にヌルクラインを描写することで、解の挙動を調べやすくなる。ここで、ヌルクラインとは、変数の微分が0になる点の集合である。本研究ではまず、Izhikevich ニューロンモデルの v, u を軸にとった相平面を作成した。次に、相平面上に $\dot{v} = 0, \dot{u} = 0$ を満たす v ヌルクラインと u ヌルクラインを描写した。相平面上において、 v ヌルクラインより上では、 $\dot{v} < 0$ であるため解軌道は v 軸の負の向きに進み、下では正の向きに進む。同様に、 u ヌルクラインより上では、 $\dot{u} < 0$ であるため解軌道は u 軸の負の向きに進み、下では正の向きに進む。このように、解軌道が進むおよその方向を知ることができる。

3.2 ISI に対する多様度指数

ISI のばらつきを定量的に評価するために、ISI に対する多様度指数を用いた。ISI の種類数を M 、総数を N とすると、多様度指数は式 (4) で定義される [7, 8]。

$$R = \frac{M}{N} \quad (4)$$

式 (4) より、 R の値が0付近のときは周期応答、 R の値が1付近のときは非周期応答だと考えられる。

3.3 ストロボ観測点

ストロボ観測点とは、周期入力のあるいくつかの位相における相平面のみを観測する手法である [11, 12]。ストロボ観測点を見ることで、応答の種類を区別することができる。具体的には、有限個の点が観測された場合は周期応答、閉曲線が観測された場合は準周期応答を意味する。ただし、リセットのある系では開曲線となる場合がある。さらに、状態値がいくつかの位相で引き延ばされ、別の位相で折り畳まれるという、引き延ばし・折り畳み構造が観測された場合はカオス応答を意味する。

4 結果

Izhikevich ニューロンモデルのパラメータを RS ($a = 0.02, b = 0.2, c = -65, d = 8, I_{DC} = 10$) とし、正弦波に対する応答を調査した。数値実験にはオイラー法 (時間ステップ 0.01) を用い、線形内挿により発火時刻を推定した [9]。はじめに、 $(A, T) = (7.5, 200), (2.5, 200)$ としたときの相平面を図 1 に示す。放物線は v ヌルクライン、直線は u ヌルクラインを表す。入力 $I(t)$ の上昇と下降に応じて v ヌルクラインも上昇、下降するため、2つの放物線を v ヌルクラインの上下動の範囲として示した。

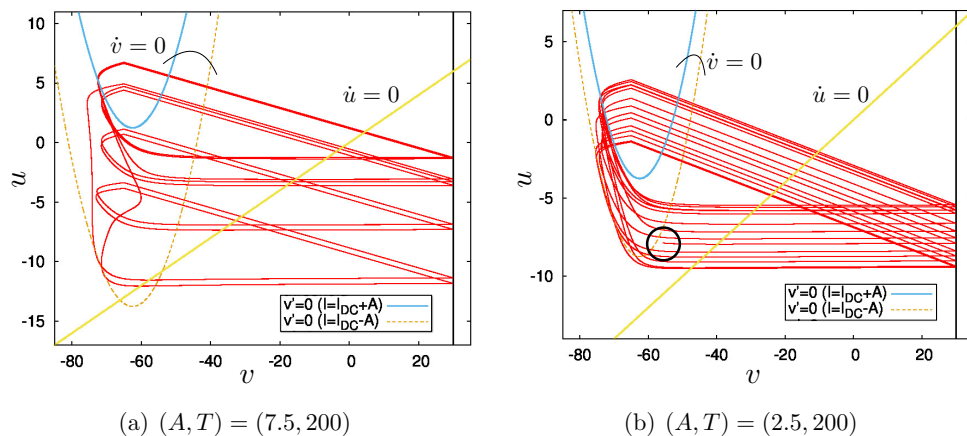


図 1: 正弦波を入力とした際の Izhikevich ニューロンモデルの相平面

図 1(a) より、解軌道は閉曲線となっていることから、この応答は周期応答である。一方、図 1(b) より、解軌道が開曲線となっている (黒丸) ことから、この応答は非周期応答である。よって、正弦波を印加した場合の Izhikevich ニューロンモデルの応答には、周期応答と非周期応答の両者が存在することが分かった。

次に、ISI に対する多様度指数 R と正弦波の振幅 A 、周期 T の関係を調べた結果を図 2 に示す。ここで、振幅を $0 \leq A \leq 10$ 、周期を $1 \leq T \leq 2,000$ [ms] の範囲で変化させた。また、ISI は小数第 2 位まで等しければ一致しているとみなした。図 2 の横軸と縦軸は正弦波の周期 T と振幅 A 、カラーバーは多様度指数 R の値である。

T が大きくなるにつれて、図 2 の周期応答の領域と非周期応答の領域の境界が $A = 6$ 付近に収束した。また、 $1 \leq T < 800$ では、 $A < 6$ でも周期応答が発生している。 $A > 6$ のときは $I(t)$ の値が下降した際に 2 つのヌルラインが交わる (図 1(a)) が、 $A < 6$ のときは交わらない (図 1(b))。 $A = 6$ のときは 2 つのヌルラインが接する。これは、図 2 の周期応答と非周期応答の領域の境界が収束する値 ($A = 6$) に対応する。

$(A, T) = (7.5, 200), (2.5, 200)$ とした際の、位相 60° ごとのストロボ観測点を図 3(a),(b) に示す。図 3 の横軸と縦軸は Izhikevich ニューロンモデルの膜電位 v と回復変数 u である。図 3(a) は多様度指数が 0 付近の周期的な応答、図 3(b) は多様度指数が 1 付近の非周期的な応答である。図 3(a) より、2 つの点が観測された。この結果は、応答が周期的であることに一致する。また、図 3(b) より、U 字型の曲線が観測されたため、応答は準周期的である。様々な振幅 A と周期 T で応答を調べた際、準周期応答でもカオス応答でもない非周期応答が確認された。一例を図 3(c) に示す。位相 $0^\circ, 60^\circ, 120^\circ, 240^\circ$ では U 字型だがリセット以外の点でも不連続であり、位相 $180^\circ, 300^\circ$ では連続となっている。

5 まとめ

本研究では、Izhikevich ニューロンモデルの周期入力に対する応答を調査するため、3 つの実験を行なった。まず、相平面上における解軌道とヌルラインを調査した。その結果、周期応答と非周期応答の両者が存在することを確認した。次に、正弦波の振幅 A と周期 T を変えて ISI の多様度指数を評価した。その結果、 $T \geq 800$ のときは $A > 6$ では周期応答となること、 $A < 6$ では非周期応答となることが分かった。さらに、ストロボ観測点を用いて、応

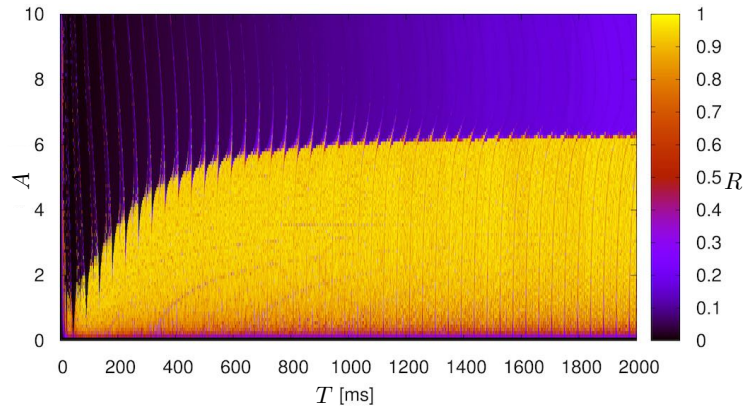


図 2: 多様度指数 R と正弦波の振幅 A 、周期 T の関係

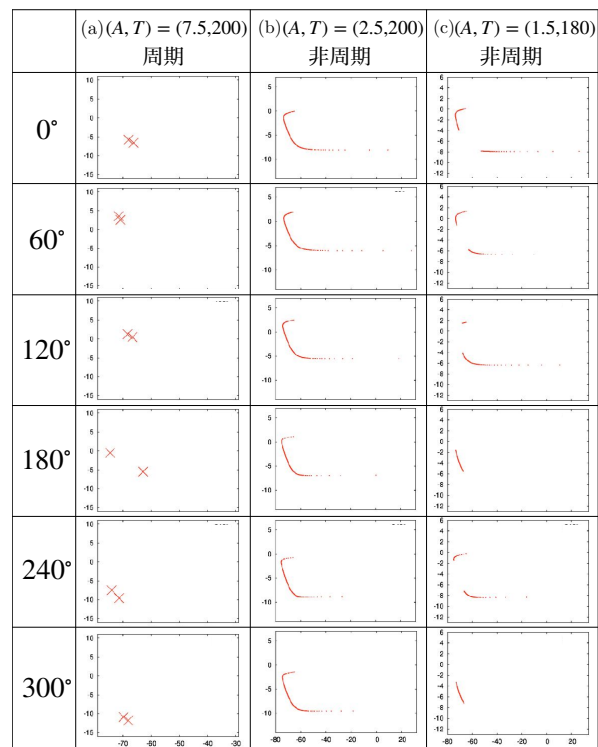


図 3: 正弦波を入力とした際の Izhikevich ニューロンモデルの応答のストロボ観測点

答の種類を定性的に調査した。その結果、非周期応答のストロボ観測点では、U字型の曲線が確認された。これは、準周期応答であることを示すものである。一方、準周期応答でもカオス応答でもない非周期応答の例も確認された。

本研究では、周期応答と準周期応答の存在は確認したが、カオス応答の特徴である引き延ばし・折り畳み構造の存在を明確にすることはできなかった。これは、Izhikevich ニューロンモデルが有するリセット機構に起因すると考えられる。よって、リセット機構を有する力学系に対するリアプノフ指数推定法 [10] などを導入することで、応答をより詳細に分析することが今後の課題である。

参考文献

- [1] H. Hayashi, S. Ishizuka, M. Ohta, and K. Hirakawa, “Chaotic behavior in the onchidium giant neuron under sinusoidal stimulation,” *Physics Letters A*, Vol. 88, No. 8, pp. 435–438, 1982.
- [2] K. Aihara, T. Numajiri, G. Matsumoto, and M. Kotani, “Structures of attractors in periodically forced neural oscillators,” *Physics Letters A*, Vol. 116, No. 7, pp. 313–317, 1986.
- [3] A. L. Hodgkin and A. F. Huxley, “A quantitative description of membrane current and its application to conduction and excitation in nerve,” *The Journal of Physiology*, Vol. 117, No. 4, pp. 500–544, 1952.
- [4] K. Aihara, G. Matsumoto, and Y. Ikegaya, “Periodic and non-periodic responses of a periodically forced Hodgkin-Huxley oscillator,” *Journal of Theoretical Biology*, Vol. 109, No. 2, pp. 249–269, 1984.
- [5] E. M. Izhikevich, “Simple model of spiking neurons,” *IEEE Transactions on Neural Networks*, Vol. 14, No. 6, pp. 1569–1572, 2003.
- [6] A. Farokhniaee and E. W. Large, “Mode-locking behavior of Izhikevich neurons under periodic external forcing,” *Physical Review E*, Vol. 95, No. 6, 062414, 2017.
- [7] 杉浦希望, 藤原寛太郎, 保坂亮介, 池口徹, “Izhikevich ニューロンモデルのカオス応答とその統計的解析,” 電子情報通信学会技術研究報告, Vol. 113, No. 116, pp. 43–48, 2013.
- [8] 内木楓, 島田裕, 藤原寛太郎, 池口徹, “Izhikevich ニューロンモデルにおけるカオス応答とカオス同期,” 電子情報通信学会論文誌 A, Vol. J100-A, No. 5, pp. 195–204, 2017.
- [9] E. M. Izhikevich, “Hybrid spiking models,” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 368, No. 1930, pp. 5061–5070, 2010.
- [10] F. Bizzarri, A. Brambilla, and G. S. Gajani, “Lyapunov exponents computation for hybrid neurons,” *Journal of Computational Neuroscience*, Vol. 35, No. 2, pp. 201–212, 2013.

発表文献

- [P1] Yota Tsukamoto, Honami Tsushima, and Tohru Ikeguchi, “Non-periodic responses of the Izhikevich neuron model with periodic inputs,” *The 2021 NonLinear Science Workshop, NLSW-54*, 2021.
- [P2] Yota Tsukamoto, Honami Tsushima, and Tohru Ikeguchi, “Non-periodic responses of the Izhikevich neuron model to periodic inputs,” to appear in *NOLTA, IEICE*, 2022.
- [P3] 塚本陽太, 對馬帆南, 池口徹, “周期入力に対する Izhikevich ニューロンモデルの応答 –Fast Spiking ニューロンの場合–,” 電子情報通信学会総大会, 発表予定, 2022.

複雑ネットワーク理論に基づく新聞記事の時間的変化の解析

平手寛之 (池口徹 教授 , Nina Sviridova 助教)

1 はじめに

近年, 計算機の発展により, 大量の文章を扱うことが可能となっている. これにより, 文章データから何らかの特徴を抽出するテキストマイニングの研究が盛んに行われている. その中でも特に, 文章を複雑ネットワークの観点から解析する研究が注目されている. 具体的には, 文章を単語同士の繋がりを持つネットワークと捉え, 複雑ネットワークとして解析を行う研究である. 例えば, 文章をネットワークに変換する際の単語の共起関係についての解析 [1], 言語のネットワーク構造と地域の関係についての解析 [2] などが行われている. しかし, 同じ共同体に所属する多数の著者が執筆を行う新聞記事などを対象とした研究はほとんど行われていない. また, 戦前の新聞記事を読解すると, 句点の数, 使用されている単語が変化している.

そこで本論文では, 戦前の 1912 年から 1944 年の新聞記事を対象として, 文章の基本的な特徴量である漢字, ひらがな, カタカナの割合と複雑ネットワーク的な指標であるクラスタ係数 [3], 四角形クラスタ係数 [3], 次数分布の傾き [4] を用いることで, 新聞社の年ごとの文章構造の特徴とその時間変化を調査した. その結果, 文章の基本的な特徴量は, 新聞社間で年ごとに異なる変化が生じること, 複雑ネットワーク的な指標は, 新聞社間で年ごとに同様に変化していることが明らかとなった. そこで, 新聞記事全体を対象として, 文章の基本的な特徴量である品詞の割合を加えることで, 年ごとの文章構造の変化を調査した. その結果, 年ごとの文章の基本的な特徴量の時間変化と, 複雑ネットワーク的な指標の時間変化は異なる傾向を示すことが分かった.

2 言語ネットワーク

本論文では, 隣接している単語を枝で結ぶことで, 重みなし無向ネットワークを作成する. ネットワークの作成例を図 1 に示す. (i) 形態素解析により, 単語の品詞情報を含めた上で原型に変形する. 形態素解析には Mecab [5] を使用した. (ii) 句読点, 半角句読点, 記号を除き, 隣同士の単語を枝で接続する. (iii) 同一品詞の単語を 1 頂点とし, ネットワークを作成する. ただし, 解析には, 含まれている頂点数が最大となる最大部分グラフを使用する.

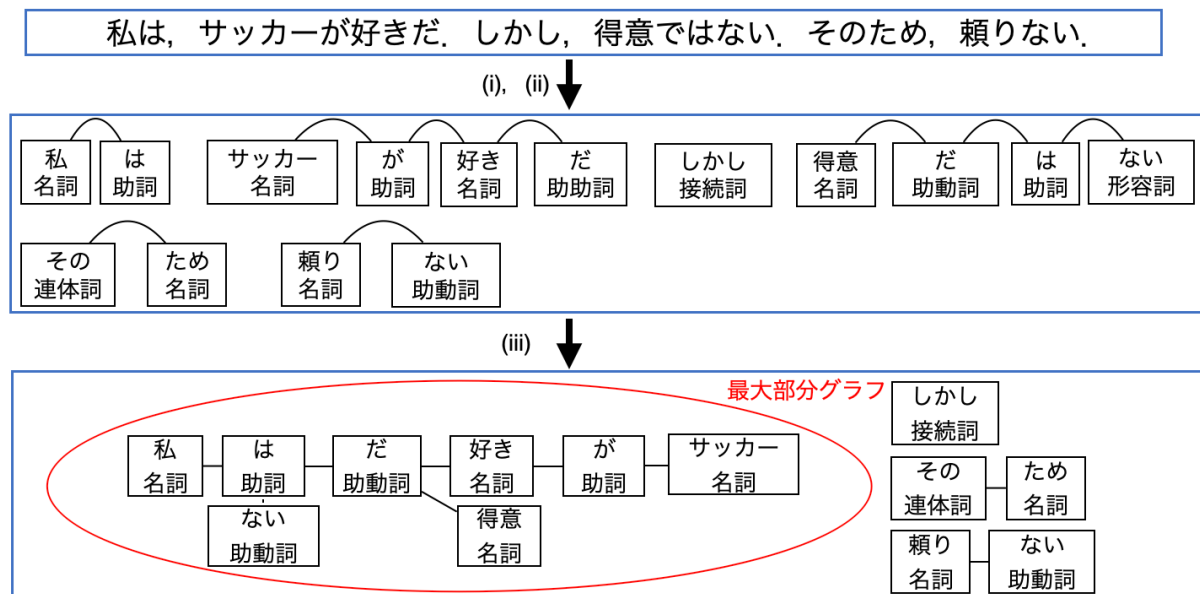


図 1: 言語ネットワーク作成例

3 使用データ

本論文では、神戸大学の新聞データ [6] の 1912 年から 1944 年の新聞記事を対象とした。使用した新聞社は、日経新聞、東京朝日新聞、東京毎日新聞、大阪朝日新聞、大阪毎日新聞、神戸新聞、東京時事新報、報知新聞、中央新聞、読売新聞の 10 社である。各新聞社ごとの記事数、一記事あたりの文字数の平均を表 III に示す。表 III から、中央新聞の記事数は他の新聞社に比べて少ないことが確認できる。

4 数値実験

4.1 各新聞社の年ごとの文章構造の比較結果

表 III に示した 10 社の新聞記事から生成した言語ネットワークの年ごとのクラスタ係数、四角形クラスタ係数、次数分布の傾きと記事内の漢字の割合、ひらがなの割合、カタカナの割合の平均とそれらの 95% 信頼区間を算出した。クラスタ係数 C_3 [3] の定義を式 (1)、四角形クラスタ係数 C_4 [3] の定義を式 (2) に示す。

$$C_3 = \frac{1}{n} \sum_{i=1}^n \frac{1}{k_i C_2} \sum_{j=1}^n A_{i,j} \sum_{t=j+1}^n A_{i,t} A_{j,t}, \quad (1)$$

$$C_4 = \frac{\sum_{i=1}^n \sum_{j=1}^{k_i} \sum_{l=j+1}^{k_i} q_{ijl}}{\sum_{j=1}^n \sum_{l=j+1}^n ((k_j - 1 - q_{ijl} - A_{j,l})(k_l - 1 - q_{ijl} - A_{j,l}) + q_{ijl})}. \quad (2)$$

ただし、 n は頂点数、 k_i は頂点 i の次数である。 A_{ij} は隣接行列の第 (i, j) 要素であり、頂点 i, j が隣接する場合は $A_{ij} = 1$ 、それ以外の場合は $A_{ij} = 0$ である。 q_{ijl} は頂点 i, j, l を含む四角形の数である。クラスタ係数 C_3 、四角形クラスタ係数 C_4 は、頂点数の異なるネットワーク同士で比較を行うため、ランダム化したネットワークのクラスタ係数 $\tilde{C}_3$ 、四角形クラスタ係数 $\tilde{C}_4$ で正規化した。結果を図 2 (a)~(f) に示す。

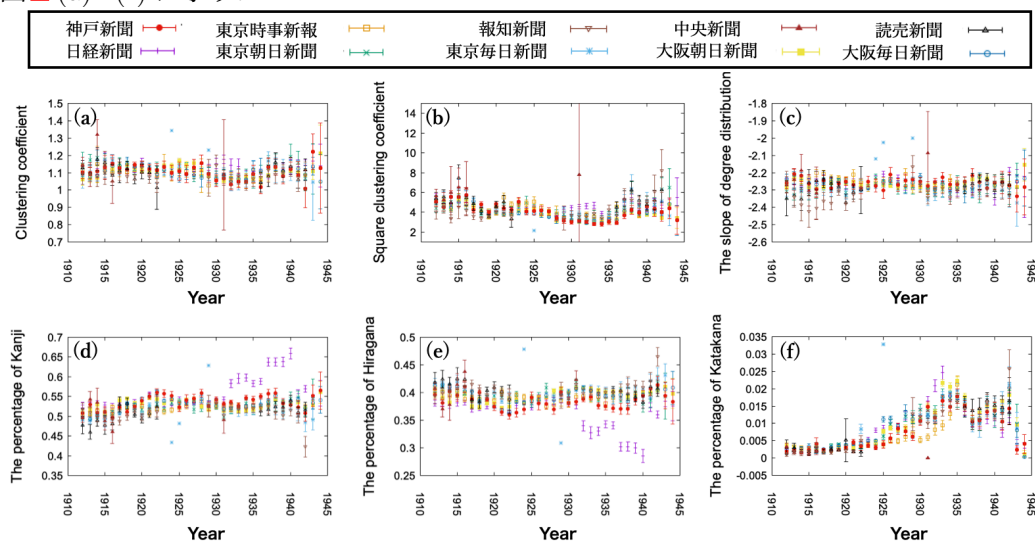


図 2: 各新聞社の (a) クラスタ係数, (b) 四角形クラスタ係数, (c) 次数分布の傾き, (d) 漢字の割合, (e) ひらがなの割合, (f) カタカナの割合の平均とその 95% 信頼区間の時間変化

図2 (d), (e)を見ると, 1930年から1940年にかけての日経新聞の漢字とひらがなの割合は, 他新聞社の信頼区間と重ならない. これは, 文章の基本的な特徴量は新聞社間で異なる傾向があることを示すものである. 一方, 図2 (f) から, カタカナの割合はどの新聞社においても各新聞社間で顕著な差は見られない. また, 図2 (a)~(c) から, クラスタ係数, 四角形クラスタ係数, 次数分布の傾きはどの新聞社においても新聞社間で大きな違いはない. これらの結果から, 文章の基本的な特徴量の変化が発生してもネットワーク構造には大きな影響を与えないと考えられる.

4.2 新聞記事の文章構造の時間変化を解析した結果

表1で示した10社の新聞データ全てを使用して, 年ごとの新聞記事内の漢字の割合, ひらがなの割合, カタカナの割合の平均とその95%信頼区間, 品詞の割合の平均とその95%信頼区間を算出した. さらに, 10社の新聞データ全てを使用して言語ネットワークを作成することで, クラスタ係数[3], 四角形クラスタ係数[3], 次数分布の傾き[4]の平均とそれらの95%信頼区間を算出し, 文章の基本的な特徴量と複雑ネットワーク的な指標を用いて, 年ごとの文章構造の遷移を調査した. 新聞記事の年ごとの漢字の割合, ひらがなの割合, カタカナの割合, 品詞の割合, クラスタ係数, 四角形クラスタ係数, 次数分布の傾きを算出した結果を図3~5に示す.

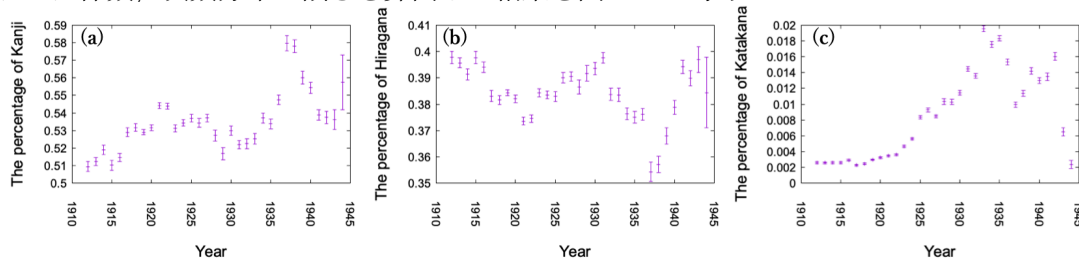


図 3: (a) 漢字, (b) ひらがな, (c) カタカナの割合の平均とその95%信頼区間の時間変化

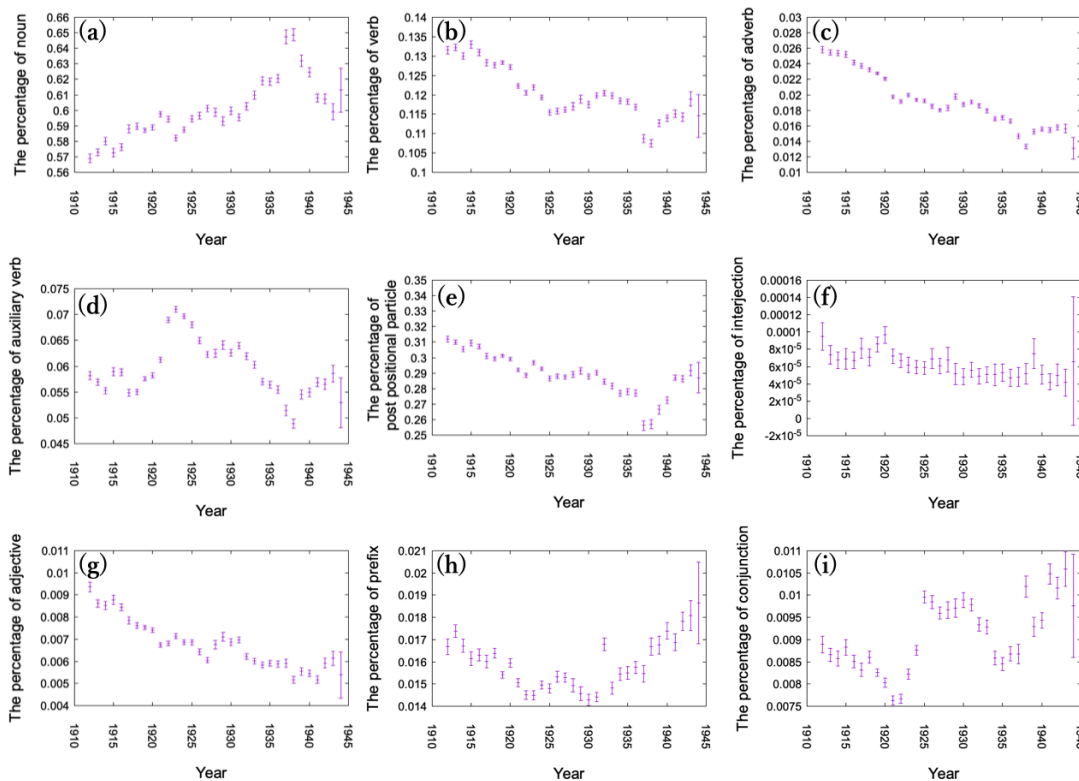


図 4: (a) 名詞, (b) 動詞, (c) 副詞, (d) 助動詞, (e) 助詞, (f) 感動詞, (g) 形容詞, (h) 接頭詞, (i) 接続詞の割合の平均とその95%信頼区間の時間変化

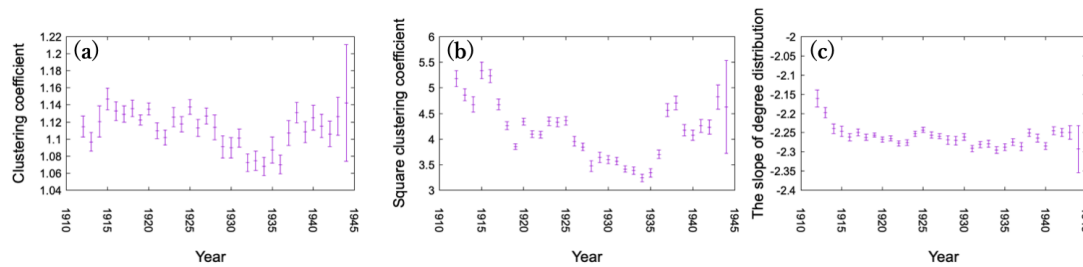


図 5: (a) クラスタ係数, (b) 四角形クラスタ係数, (c) 次数分布の傾きの平均と 95%信頼区間の時間変化

図 3 (a)~(c) より, 漢字, ひらがなの割合は, 1920 年, 1930 年, 1938 年, 1942 年にかけて上下に変動している. 一方, カタカナの割合は, 1935 年にかけて上昇し, 1944 年にかけて下降する. また, 図 4 (a)~(i) より, 名詞の割合は, 1938 年にかけて上昇し, それ以降は下降する. また, 動詞, 副詞, 助詞, 形容詞の割合は年ごとに下降し, 助動詞, 接頭詞, 接続詞は上下に変動している. さらに, 図 5 (a)~(c) より, クラスタ係数は, 1915 年, 1922 年, 1925 年, 1935 年, 1940 年にかけて上下の変動を繰り返している. また, 四角形クラスタ係数は, 年ごとに細かく変化しており, 次数分布の傾きは, 大きな変化はない. これらの結果から, 文章の基本的な特徴量である漢字, ひらがな, カタカナ, 品詞の割合と複雑ネットワーク的な指標であるクラスタ係数, 四角形クラスタ係数, 次数分布の傾きの変化は互いに異なっていることが分かった. 従って, 文章の解析には文章の基本的な特徴量だけでなく, 複雑ネットワーク的な指標を用いた調査も重要である.

5 まとめ

本論文では, 1912 年から 1944 年の 10 社の新聞データに対して, 文章の基本的な特徴量, 複雑ネットワーク的な指標を用いて年ごとの各新聞社の比較と年ごとの新聞記事全体の文章構造の時間変化を調査した. 新聞社の比較を行なった結果, 文章の基本的な特徴量は, 日経新聞が他の新聞社と異なるが, 複雑ネットワーク的な指標は, 新聞社間には大きな違いはないことが分かった. また, 年ごとの文章構造の変化を調査した結果, 文章の基本的な特徴量である漢字, ひらがな, カタカナ, 品詞の割合の年ごとの変動と複雑ネットワーク的な指標であるクラスタ係数, 四角形クラスタ係数, 次数分布の傾きの年ごとの変動が異なることが分かった. 今後は, 文章構造の変化が発生した社会的要因などについて調査を行うことで, 文章構造の時間変化をより詳細に検討することが必要である.

参考文献

- [1] R. F. Cancho and R. V. Solé, “The small world of human language,” *Proceedings of the Royal Society of London. Series B: Biological Sciences*, Vol. 268, No. 1482, pp. 2261–2265, 2001.
- [2] N. Shijulal et al., “Networks uncover hidden lexical borrowing in Indo-European language evolution,” *Proceedings of the Royal Society B: Biological Sciences*, Vol. 278, No. 1713, pp. 1894–1803, 2011.
- [3] P. G. Lind, M. C. Gonzalez, and H. J. Herrmann, “Cycles and clustering in bipartite networks,” *Physical Review E*, Vol. 72, No. 5, pp. 056127, 2005.
- [4] A. Clauset, C. R. Shalizi, and M. E. Newman, “Power-law distributions in empirical data,” *SIAM Review*, Vol. 51, No. 4, pp. 661–703, 2009.
- [5] “MeCab: Yet Another Part-of-Speech and Morphological Analyzer,” <http://taku910.github.io/mecab/> (最終閲覧日: 2021 年 12 月 10 日)
- [6] “神戸大学附属図書館,” <http://www.lib.kobe-u.ac.jp/sinbun/> (最終閲覧日: 2021 年 9 月 7 日)

発表文献

- [P1] 松本 朋子, 平手 寛之, 島田 裕, 池口 徹, “新聞記事から見る戦前世論の対外姿勢”, 2022 年度日本政治学会研究大会, 2022 年 10 月, 投稿中.

Colexification ネットワークにおける基本的感情に関する研究

福家水月 (池口徹 教授 , Nina Sviridova 助教)

1 はじめに

近年, 自然言語処理の分野において感情に関する研究が行われている. その中でも特に, colexification を用いて感情分類を行った研究が注目されている [1]. Colexification とは, ある単語が複数の概念を有する現象である. 例えばスペイン語において “malo” という単語は “BAD (悪い)” と “SEVERE (厳しい)” の二つの概念を意味し, これらは colexification を形成する. ある言語において, colexification を形成する複数の概念は意味が類似する傾向にある. このような観点から, colexification は言語の意味論的な研究に用いられている [2].

Colexification を用いて作成されたネットワークを colexification ネットワークと呼ぶ. Colexification ネットワークは, 頂点を概念, colexification を枝とすることで作成される. また, colexification ネットワークにおける, 感情を表す概念に対応する頂点について調査を行うことで, 自然言語処理の観点における感情について考察できる. 文献 [3] では, ランダムウォークを用いて, 感情を表す概念間の経路長を最小化した colexification ネットワークを作成している. また, 作成したネットワークから, 感情を表す概念で構成されるコミュニティを検出することで感情を分類している. しかし, ネットワークにおける基本的感情を表す概念については議論されていない.

そこで本研究では, ランダムウォークのステップ数を増加させることで, 感情以外を表す概念の影響を最大化したネットワークを作成し, colexification ネットワークにおける基本的感情に関する調査を行った. 調査の結果, “GOOD,” “WANT,” “BAD,” “LOVE” の4つの概念で表される感情が, colexification ネットワークにおける基本的感情であることを確認した.

2 ネットワークの作成法

概念を頂点, colexification を形成する2つの概念を枝で結ぶことで, colexification ネットワークを作成する. ここで, 頂点 i と j を結ぶ枝の重みを W_{ij} とし, W_{ij} を i と j に対応する概念の間に colexification が存在する言語の数とする. 図 1 はスペイン語の “malo”, フランス語の “mauvais”, ロシア語の “дурной” において colexification を形成している概念 “BAD,” “SEVERE,” “UGLY” から, colexification ネットワークが作成される様子を示している.

図 1 の “SEVERE” と “UGLY” のように, 概念同士に枝が存在しない場合がある. しかし, これらの2つの概念はどちらも “BAD” と colexification を形成している. そのため, “SEVERE” と “UGLY” も類似性を持ち, 間接的に colexification を形成していると考える. このような間接的な関係性を定量化し, 枝の重みに反映させるために, 作成したネットワークに対してランダムウォークを適用させる.

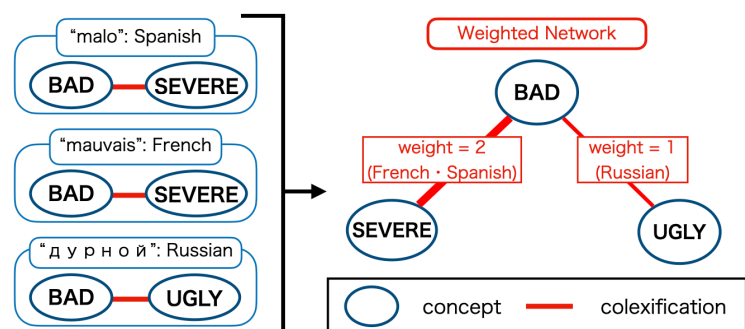


図 1: Colexification ネットワークの作成例

ランダムウォークは枝で繋がる頂点間を遷移確率行列 $P = [P_{ij}]$ に基づいて移動する手法である. Colexification ネットワークの頂点数を N とおくと, $P_{ij} = W_{ij} / \sum_{s=1}^N W_{is}$ と定義される. また, n ステップ後の遷移確率行列は P^n となる.

文献 [11] では, colexification ネットワークとランダムウォークを用いて, 以下の手順で colexification ネットワーク $G_{C(n)}$ を作成している.

1. CLICS³ [3] のデータを用いて, 図 1 のように colexification ネットワークを作成する. CLICS³ とは, 3,061 個の言語における colexification を収録したデータベースである.
2. 作成した colexification ネットワークに対してステップ数 $n = 1, \dots, 5$ でランダムウォークを適用し, 遷移確率行列 $P^1, \dots, P^5$ を作成する.
3. ネットワーク $G_{B(n)}$ の重み付き隣接行列 $B(n) = \sum_{s=1}^n P^s$ を定義する.
4. ネットワーク $G_{B(n)}$ における, 代表的な感情の概念に対応する頂点と, その頂点を結ぶ枝を抽出することで新たにネットワーク $G_{C(n)}$ を作成する (図 2).

ランダムウォークにおいてステップ数が $n = 5$ である場合, $G_{C(n)}$ が初めて完全グラフとなる. このことから, $n = 5$ の場合, ネットワーク中の感情を表す概念に対応する頂点間の経路において, 感情以外を表す概念に対応する頂点を経由する経路長が最小となる. 文献 [11] では, ネットワーク $G_{C(n)}$ を解析することで, 感情を表す概念のコミュニティ構造を調査している. しかし, $n = 5$ の場合, 感情を表す概念間を繋ぐ経路に現れる頂点 (概念) の数は高々5つであるため, 6 ステップ以上離れた頂点 (概念) の影響は考慮されていない.

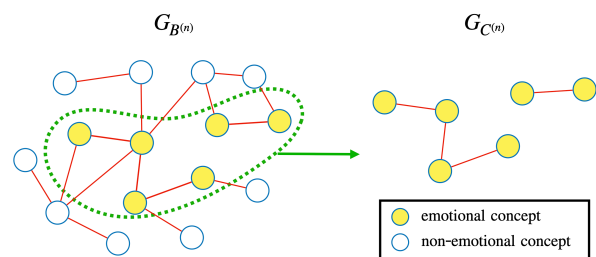


図 2: ネットワーク $G_{C(n)}$ の作成例

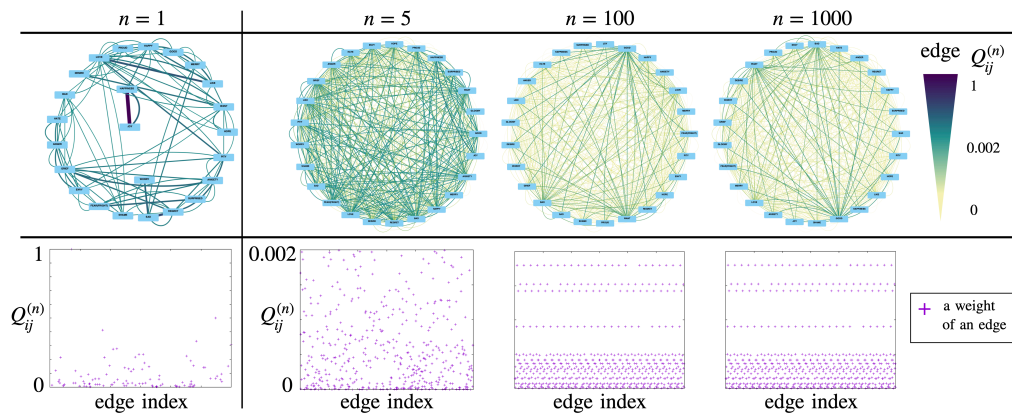
3 Colexification ネットワークの解析

本研究では, 感情を表す概念間を繋ぐ経路において, 感情以外を表す概念の影響を最大にしたネットワーク $G_{Q(n)}$ を以下の手順で作成した.

1. CLICS³ のデータを用いて, 図 1 のように colexification ネットワークを作成する. ここで, 作成されたネットワークを G_W とおく. また, ネットワーク G_W の頂点数を N_W とおく.
2. 作成したネットワークに対して遷移確率行列 P に基づくランダムウォークを $n = 1, \dots, 1000$ ステップ適用し, 遷移確率行列 $P^1, \dots, P^{1000}$ を作成する.
3. 遷移確率行列 P^n を重み付き隣接行列としたネットワーク G_{P^n} から, 代表的な感情の概念に対応する頂点と, その頂点を結ぶ枝のみを抽出した有向重み付きネットワーク $G_{Q(n)}$ を作成する. ここで, ネットワーク $G_{Q(n)}$ の重み付き隣接行列を $Q(n)$ とする. また, ネットワーク $G_{Q(n)}$ の頂点数を $N_{Q(n)}$ とおく.

本研究では, 以上の手順で作成されたネットワーク $G_{Q(n)}$ の可視化を行った. 作成したネットワーク $G_{Q(n)}$ を図 3 の上段に, ネットワーク $G_{Q(n)}$ における枝重みの分布を下段に示す.

図 3 から, n の増加に伴ってネットワークの枝重みが一定値に収束する傾向が示された. また, 図 3 下図より, 同じ重みを持つ枝が複数存在することも分かる. これらの同じ重みを持つ枝は全て同じ頂点に向かう枝であることが判明した. また, これらの枝のうち, 特に値が大きいものは “GOOD,” “WANT,” “BAD,” “LOVE” の 4 つの概念に対応する頂点に接続する枝で構成されていることを確認した. このことから, これらの 4 つの頂点が colexification ネットワークにおいてハブとなっている可能性がある.

図 3: n ステップにおけるネットワークと枝重みの分布

Colexification ネットワークにおいてハブとなる概念は、多くの概念と類似している傾向がある。そこで本研究では、ネットワーク $G_{Q(1000)}$ においてハブとなる概念が、colexification ネットワークにおける基本的感情を表す概念であると定義する。具体的には、以下の手順でネットワーク $G_{Q(n)}$ におけるハブを定義した。まず、頂点 i に向かう枝の強度 $\text{In}_i^{(n)}$ を $\text{In}_i^{(n)} = \sum_{j=1}^{N_{Q(n)}} Q_{ji}^{(n)} (j \neq i)$ とする。次に、強度 $\text{In}_i^{(n)}$ を降順に並べた際の頂点 i の順位を r_i とおく。さらに、強度 $\text{In}_i^{(n)}$ 、順位を r_i を用いて、頂点 i における強度 $\text{In}_i^{(n)}$ の変化率 θ_i を $\theta_i = \text{In}_i^{(n)} / \text{In}_j^{(n)}$ で求める。ここで、頂点 j について $r_j = r_i + 1$ を満たすものとする。最後に、ネットワークにおける強度 $\text{In}_i^{(n)}$ が大きい頂点のうち、変化率 θ_i が最も大きい頂点を a とし、 $r_i < r_a$ を満たす頂点をハブと定義する。

ネットワーク $G_{Q(1000)}$ における、頂点 i の強度 $\text{In}_i^{(1000)}$ 、順位 r_i 、変化率 θ_i を表 1 に示す。表 1 の結果より、ネットワーク $G_{Q(1000)}$ においてハブとなる頂点は“GOOD,” “WANT,” “BAD,” “LOVE”の4つの概念に対応する頂点であることが分かる。即ち、colexification ネットワークにおける基本的感情は“GOOD,” “WANT,” “BAD,” “LOVE”の4つの概念が表す感情である。

また、本研究では、ネットワーク G_W においてどのような頂点がネットワーク $G_{Q(1000)}$ でハブと

表 1: Colexification ネットワークにおける次数と強度

r_i	vertex i	$\text{In}_i^{(1000)}$	θ_i	k_i	g_i
1	GOOD	4.49×10^{-2}	1.18	126	420
2	WANT	3.81×10^{-2}	1.07	156	356
3	BAD	3.55×10^{-2}	1.57	72	332
4	LOVE	2.26×10^{-2}	1.81	96	211
5	FEAR(FRIGHT)	1.25×10^{-2}	1.03	42	117
6	GRIEF	1.21×10^{-2}	1.16	35	113
7	LIKE	1.04×10^{-2}	1.00	27	97
8	HAPPY	1.04×10^{-2}	1.14	61	97
9	HATE	9.10×10^{-3}	1.01	59	85
10	DESIRE	9.00×10^{-3}	1.14	51	84
11	ANGER	7.92×10^{-3}	1.03	46	74
12	HOPE	7.68×10^{-3}	1.04	25	66
13	REGRET	7.39×10^{-3}	1.19	31	69
14	ANXIETY	6.21×10^{-3}	1.16	19	58
15	SHAME	5.35×10^{-3}	1.31	43	50
16	PITY	4.07×10^{-3}	1.12	13	38
17	ENVY	3.64×10^{-3}	1.00	13	34
18	PROUD	3.64×10^{-3}	1.89	20	34
19	SURPRISED	1.93×10^{-3}	1.13	13	18
20	SAD	1.71×10^{-3}	1.23	9	16
21	HAPPINESS	1.39×10^{-3}	1.85	6	13
22	MERRY	7.50×10^{-4}	1.75	7	7
23	JOY	4.28×10^{-4}	1.33	1	4
24	WORRY	3.21×10^{-4}	3.00	3	3
25	GLOOMY	1.07×10^{-4}		1	1

なるかについても調査を行った。ネットワーク G_W において、隣接行列 A を式 (1) で定義する。

$$A_{ij} = \begin{cases} 1 & (W_{ij} \neq 0) \\ 0 & (W_{ij} = 0) \end{cases} \quad (1)$$

A を用いると、ネットワーク G_W における頂点 i の次数 k_i は、 $k_i = \sum_{j=1}^{N_W} A_{ij}$ となる。また、ネットワーク G_W における頂点 i の強度 g_i は $g_i = \sum_{j=1}^{N_W} W_{ij}$ で求めることができる。ネットワーク G_W における次数 k_i 、強度 g_i を表 1 の右 2 列に示す。

表 1 から、ネットワーク $G_{Q(1000)}$ における強度 $\text{In}_i^{(1000)}$ で大きい値をとる頂点は、ネットワーク G_W における次数 k_i と強度 g_i でも大きい値をとることがわかる。従って、colexification ネットワークにおいてハブとなる頂点に対応する概念は、より多くの colexification を成す概念であることが示された。

4 まとめと今後の課題

本研究では、同じ単語が複数の概念を意味する現象である colexification を用いてネットワークを作成した。作成したネットワークに対してステップ数 $n = 1000$ でランダムウォークを適用させ、感情以外を表す概念との関係を反映させた感情の概念のネットワークを作成した。ランダムウォークによって作成されたネットワークに対して調査を行った結果、“GOOD,” “WANT,” “BAD,” “LOVE” の 4 つの概念に対応する頂点がハブとなっていることを確認した。この結果は、これらの 4 つの概念で表される感情が colexification ネットワークにおける基本的感情であることが示すものである。また、ハブとなる頂点の次数と強度に着目したところ、より多くの colexification を形成する概念が、ネットワークにおいてハブとなる頂点に対応する概念であることがわかった。

本研究では、全ての言語における colexification を用いてネットワークを作成した。今後は、語族別に colexification ネットワークを作成することで、語族間の colexification の差異などを明らかにする予定である。

参考文献

- [1] J. C. Jackson, *et al.*, “Emotion semantics show both cultural variation and universal structure,” *Science*, Vol. 366, No. 6472, pp. 1517–1522, 2019.
- [2] A. François, “Semantic maps and the typology of colexification: Intertwining polysemous networks across languages,” *From Polysemy to Semantic Change: Towards a Typology of Lexical Semantic Associations*, John Benjamin Publishing, pp. 163–215, 2008.
- [3] J. M. List, *et al.*, “The Database of Cross-Linguistic Colexifications, reproducible analysis of cross-linguistic polysemies,” <https://clics.clld.org/>, (最終閲覧日 2021 年 12 月 3 日).

発表文献

- [P1] Mitsuki Fukuya, Tomoko Matsumoto, Yutaka Shimada, and Tohru Ikeguchi, “An investigation about basic emotions using hubs in a network of colexification,” to appear in *Proc. of RISP International Workshop on Nonlinear Circuits, Communications and Signal Processing*, 2022.
- [P2] 福家水月, 松本朋子, 島田裕, 池口徹, Colexification ネットワークにおける感情とハブ, 電気情報通信学会総合大会, 発表予定, 2022.

マーク付点過程に対する重み付き Visibility Graph に関する研究

森太紀 (池口徹 教授 , Nina Sviridova 助教)

1 はじめに

実世界には、経済指標、天気、地震、楽譜などの様々な時系列データが存在する．時系列データ解析の新たなアプローチとして、時系列データを複雑ネットワークに変換して解析する手法が研究されている [1–3]．本研究では、その手法の 1 つである Visibility Graph (VG 法) [3] を用いている．VG 法の概略を図 1 に示す．はじめに、時刻 t_i における時系列の値を y_i とする (図 1(a))．これが、作成されるネットワークの頂点 v_i に対応する．任意の 2 つのデータ (t_i, y_i) , (t_j, y_j) が互いに視認できるならば、頂点 v_i , v_j を結ぶ (図 1(b), (c))．具体的には次のいずれかの条件を満たせば良い．

- (i) データ (t_i, y_i) , (t_j, y_j) が連続する 2 つのデータである．
- (ii) $i < k < j$ を満たす全てのデータ (t_k, y_k) について式 (1) を満たす．

$$y_k < y_i + (y_j - y_i) \frac{t_k - t_i}{t_j - t_i} \quad (1)$$

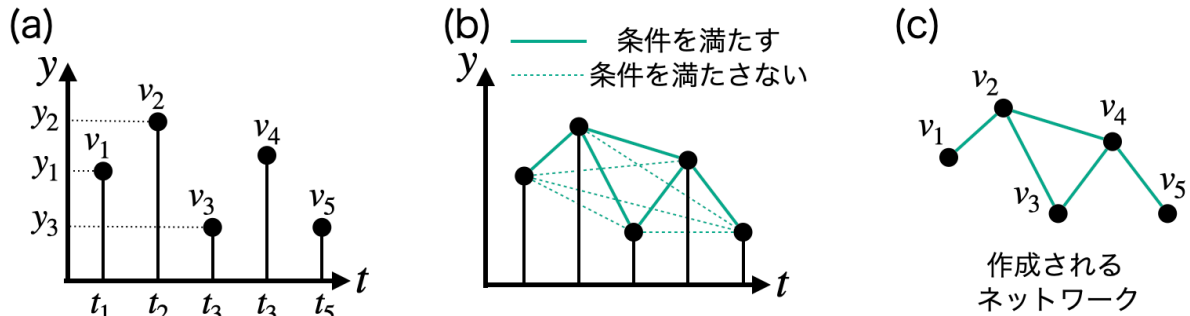


図 1: VG 法の手順

従来の VG 法では、その多くがデータの時間間隔が一定である時系列 (Equally sampled Time Series, 以下 ETS) に対して適用されている．しかし、実世界のデータの多くは、時間間隔が一定ではないマーク付点過程 (Marked Point Process, 以下 MPP) として観測される．即ち、VG 法の MPP への適用可能性を検討することも重要である．そこで本論文では、VG 法を用いて MPP の時間間隔情報をネットワークに反映するために、イベント間距離の逆数を用いたネットワークの重み付け手法を提案した．

2 解析対象の時系列の作成手法

本稿では、式 (2) に示す修正ベルヌーイ写像 [4] より 2 種類の方法を用いて局所的にイベントが密集する MPP を作成した．

$$x(n+1) = \begin{cases} x(n) + 2^{B-1}(1-2\varepsilon)x(n)^B + \varepsilon & (0 \leq x(n) \leq \frac{1}{2}) \\ x(n) - 2^{B-1}(1-2\varepsilon)(1-x(n))^B - \varepsilon & (\frac{1}{2} \leq x(n) \leq 1) \end{cases} \quad (2)$$

ただし、修正ベルヌーイ写像のパラメータは $B = 2$, $\varepsilon = 1 \times 10^{-13}$ とした．1 つ目の手法では、図 2(a) に示すように、修正ベルヌーイ写像の値を作成する MPP の時間間隔に割り当てる手法である

(Values to Inter Event Interval, 以下, V-IEI). 修正ベルヌーイ写像の時刻 n における状態値を $x(n)$ とすると, 作成する MPP の i 番目のイベント発生時刻 t_i は $t_i = \sum_{j=1}^i x(j)$ となる. 2つ目の手法では, 図 2(b) に示すように, 修正ベルヌーイ写像の状態値 $x(n)$ と $x(n+1)$ を接続する線が 0.5 と交わる時刻を MPP のイベント発生時刻とする手法である (内挿). いずれの手法においても作成した MPP のデータ数 N は 2,000 とし, マーク値 m_i は区間 $[0, 1]$ の一様乱数で決定した. また, 各手法を用いて MPP を作成した後, MPP のマーク値が同じで時間間隔を 1 とした ETS (ETS-1), および, 時間間隔を $T/(N-1)$ とした ETS (ETS-2) を作成した. ここで, T は MPP の観測時間 ($T = t_N - t_1$) である.

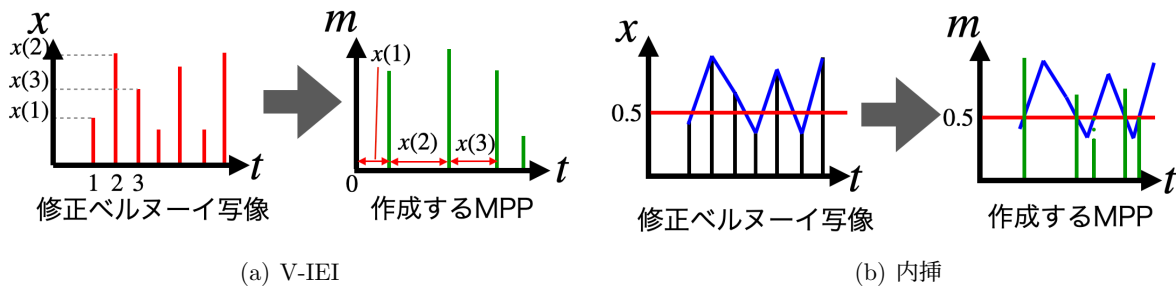


図 2: 修正ベルヌーイ写像の性質を利用した MPP の作成手法

3 VG 法を用いた重み付きネットワークの作成手法

修正ベルヌーイ写像より作成した MPP と, 時間間隔を一定に変換した ETS-1, ETS-2 に対して, VG 法を用いて重み付きネットワークに変換した. その際, 時系列上での i 番目のイベントと j 番目のイベント間距離 $l_{ij} = \sqrt{(t_i - t_j)^2 + (m_i - m_j)^2}$ を頂点 v_i, v_j 間の重みとする. 具体的な重み付け手法を式 (3) に示す.

$$w_{ij} = l_{\min} / l_{ij} \quad (3)$$

ただし, $l_{\min}$ は l_{ij} の最小値である. なお, 文献 [5] では, 式 (4) に示すように既にイベント間距離 l_{ij} を用いた重みが提案されている.

$$w_{ij} = l_{ij} / l_{\max} \quad (4)$$

ただし, $l_{\max}$ は l_{ij} の最大値である. 本論文では, VG 法を用いて得られたネットワークに対して, 式 (3) の提案法を適用した場合と式 (4) の文献 [5] の手法を適用した場合を比較した.

4 重み付きネットワークの定量化指標

本論文では, ネットワーク構造を定量化する指標を用いて MPP から作成された重み付きネットワークと, ETS から作成された重み付きネットワークに構造の差異があるか比較した. なお, 重み付きネットワークの構造を定量化する指標は式 (5) に示す重み付き平均頂点間距離 L_w [6] と, 式 (6)–(9) の重み付きクラス係数 $C_{w,i}^{(Z)}$, $C_{w,i}^{(L)}$, $C_{w,i}^{(B)}$, $C_{w,i}^{(O)}$ [7–10] である.

$$L_w = \frac{1}{N C_2} \sum_{i=1}^N \sum_{j=1, j \neq i}^N d_{w,ij} \quad (5)$$

$$C_{w,i}^{(Z)} = \frac{\sum_{j=1}^N \sum_{l=1}^N w_{ij} w_{jl} w_{li}}{(\sum_{j \neq i}^N w_{ij})^2 - \sum_{i \neq j}^N w_{ij}^2} \quad (6)$$

$$C_{w,i}^{(L)} = \sum_{j \neq l \in N_G(i)} w_{jl} \frac{1}{k_i (k_i - 1)} \quad (7)$$

$$C_{w,i}^{(B)} = \frac{\sum_{j=1}^N \sum_{l=1}^N (w_{ij} + w_{il}) a_{ij} a_{il} a_{jl}}{2s_i (k_i - 1)} \quad (8)$$

$$C_{w,i}^{(O)} = \frac{\sum_{j=1}^N \sum_{l=1}^N (w_{ij} w_{jl} w_{li})^{1/3}}{k_i C_2} \quad (9)$$

ただし、 $d_{w,ij}$ は重みを考慮した頂点 v_i, v_j 間の最短経路、 $N_G(i)$ は頂点 v_i に隣接する頂点と、その頂点間の枝のみで構成されるネットワークを表す。また、 k_i は頂点 v_i に接続する枝の数、 s_i は頂点 v_i に接続する枝の重みの総和 $s_i = \sum_{j=1}^N w_{ij}$ を表す。

5 数値実験

本研究の実験手順を以下に示す。

- (i) 修正ベルヌーイ写像を利用した MPP(V-IEI, 内挿) と、MPP から変換した ETS-1, ETS-2 を作成する。
- (ii) 作成した時系列に対し、VG 法を用いて重み付きネットワークを作成する。
- (iii) 重み付きネットワークを定量化する指標を用いて、MPP の時間間隔がネットワークに反映されているかを調査する。

100 通りの初期値から発生させた時系列を提案法を用いることで得た重み付きネットワークについて、各指標の平均値と 95%信頼区間を表 1 に示す。また、文献 [5] の手法を用いた重み付きネットワークについて、各指標の平均値と 95%信頼区間を表 2 に示す。

表 1: 提案法による重み付けネットワークの各指標の平均値と 95%信頼区間

	V-IEI			内挿		
	MPP	ETS-1	ETS-2	MPP	ETS-1	ETS-2
L_w	0.033±0.003	0.988±0.003	0.853±0.027	0.281±0.003	0.988±0.003	1.051±0.027
$C^{(Z)}$	0.011±0.001	0.373±0.000	0.335±0.010	0.152±0.001	0.373±0.000	0.386±0.010
$C^{(L)}$	0.099±0.001	0.368±0.000	0.326±0.010	0.132±0.001	0.368±0.000	0.384±0.010
$C^{(B)}$	0.736±0.002	0.719±0.000	0.724±0.002	0.714±0.002	0.719±0.000	0.717±0.002
$C^{(O)}$	0.008±0.001	0.427±0.000	0.369±0.013	0.140±0.001	0.427±0.000	0.448±0.013

表 2: 文献 [5] による重み付けネットワークの各指標の平均値と 95%信頼区間

	V-IEI			内挿		
	MPP	ETS-1	ETS-2	MPP	ETS-1	ETS-2
L_w	0.747±0.045	0.813±0.044	0.813±0.043	0.765±0.045	0.823±0.044	0.823±0.043
$C^{(Z)}$	0.007±0.004	0.005±0.000	0.007±0.004	0.003±0.004	0.005±0.000	0.005±0.004
$C^{(L)}$	0.005±0.004	0.003±0.000	0.005±0.004	0.002±0.004	0.003±0.000	0.003±0.004
$C^{(B)}$	0.754±0.001	0.766±0.000	0.763±0.001	0.761±0.002	0.766±0.000	0.767±0.004
$C^{(O)}$	0.004±0.004	0.002±0.000	0.004±0.004	0.001±0.004	0.002±0.000	0.002±0.004

表 1, 2 において, $C_w^{(X)} = (\sum_{i=1}^N C_{w,i}^{(X)})/N$, ($X \in \{Z, L, B, O\}$) である. 表 1 より, 提案法を適用した場合, $C_w^{(B)}$ を除く各指標において MPP と ETS-1, ETS-2 から作成されるネットワークには有意差があることが分かる. 一方, 表 2 より, 文献 [5] の重み付けを用いた場合, 各指標において MPP と ETS-1, ETS-2 から作成されるネットワーク間に有意差はない. これらの結果から, 提案法は MPP の時間間隔情報を適切に重み付きネットワークに反映できていると考えられる.

6 まとめ

本論文では, はじめに, 修正ベルヌーイ写像の性質を用いた 2 種類の MPP を作成した. 次に, MPP のマーク値が同じで時間間隔が 1 である時系列, および, 時間間隔が $T/(N-1)$ である時系列を作成した. 最後に, 得られた時系列に対し, VG 法を用いて重み付きネットワークに変換して複雑ネットワーク理論の観点から解析した. その際, ネットワークの枝の重みにはイベント間距離を使用する手法を提案した. その結果, 提案法を用いて重み付きネットワークを作成することで, MPP の時間間隔情報がネットワーク構造に反映されることがわかった.

参考文献

- [1] V. M. Eguiluz, D. R. Chialvo, G. A. Cecchi, M. Baliki, and A. V. Apkarian, “Scale-free brain functional networks,” *Physical Review Letters*, Vol. 94, No. 1, 018102, 2005.
- [2] J. Zhang and M. Small, “Complex network from pseudoperiodic time series: Topology versus dynamics,” *Physical Review Letters*, Vol. 96, No. 23, 238701, 2006.
- [3] L. Lacasa, B. Luque, F. Ballesteros, J. Luque, and J. C. Nuño, “From time series to complex networks: The visibility graph,” *Proceedings of the National Academy of Sciences*, Vol. 105, No. 13, pp. 4972–4975, 2008.
- [4] Y. Aizawa and T. Kohyama, “Asymptotically non-stationary chaos,” *Progress of Theoretical Physics*, Vol. 71, No. 4, pp. 847–850, 1984.
- [5] M. Zheng, S. Domanskyi, C. Piermarocchi, and G. I. Mias, “Visibility graph based temporal community detection with applications in biological time series,” *Scientific Reports*, Vol. 11, No. 1, pp. 1–12, 2021.
- [6] X. J. Xu, Z. X. Wu, and Y. H. Wang, “Properties of weighted complex networks,” *International Journal of Modern Physics C*, Vol. 17, No. 04, pp. 521–529, 2006.
- [7] B. Zhang and S. Horvath, “A general framework for weighted gene co-expression network analysis,” *Statistical Applications in Genetics and Molecular Biology*, Vol. 4, No. 1, 2005.
- [8] L. Lopez-Fernandez, G. Robles, and J. M. Gonzalez-Barahona, “Applying Social Network Analysis to the Information in CVS Repositories,” *Proceedings 1st International Workshop on Mining Software Repositories MSR 2004*, Vol. 2004, pp. 101–105, 2004.
- [9] A. Barrat, M. Barthélemy, R. Pastor-Satorras, and A. Vespignani, “The architecture of complex weighted networks,” *Proceedings of the National Academy of Sciences*, Vol. 101, No. 11, pp. 3747–3752, 2004.
- [10] J. P. Onnela, J. Saramäki, J. Kertész, and K. Kaski, “Intensity and coherence of motifs in weighted complex networks,” *Physical Review E*, Vol. 71, No. 6, 065103, 2005.

発表文献

- [P1] 森太紀, 對馬帆南, Nina Sviridova, 池口徹, “マーク付点過程に対する重み付き Visibility Graph,” 電子情報通信学会 2022 年総合大会, 2022 年 3 月発表予定.

非線形ワークショップ

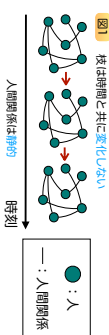
E15

コンタクトの発生順番が情報拡散率に与える影響の解析

非線形動的ネットワーク
池口研究室
NONLINEAR DYNAMICAL NETWORK
池口研究室

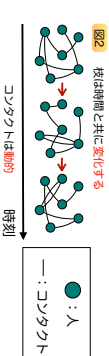
1 研究背景

● 静的なネットワーク上での情報拡散



数値実験と社会実験は近年盛んに行われている(1-4)
数値実験で社会実験の結果を再現できている(3, 4, 5)

● テンポラルネットワーク上での情報拡散



感染症拡散の研究では用いられているが、
それと類似した情報拡散の研究では用いられていない

2 研究目的

研究目的

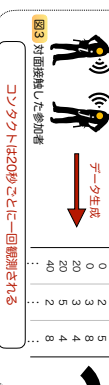
動的なテンポラルネットワーク上での
情報拡散のダイナミクスを明らかにする

情報拡散モデルを使用

研究手段
実世界のテンポラルネットワーク上で
情報拡散の数値実験を行うことで解析

3 コンタクトデータとテンポラルネットワーク(5-7)

コンタクトデータの生成方法



テンポラルネットワークの生成手法



使用したコンタクトデータ
(1) 高校でのコンタクトデータ (参加者数: 126人)
(2) 病院でのコンタクトデータ (参加者数: 75人)



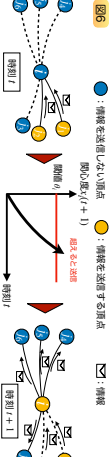
4 情報への関心度に着目した情報拡散モデル(4, 5)

関心度 減衰関数

$$x_i(t+1) = g_i(\tau_i)x_i(t) + \alpha H(x_i(t) - \theta_i) \sum_{j \in G(i)} F_j(x_j(t) - \theta_j)$$

τ_i : 減衰係数 ($0 < \tau_i < 1$) α : 情報の影響力 F_j : ステップ関数
 $G(i)$: 時刻 t での頂点 i の隣接頂点の集合 θ_i : 頂点 i の関心度の閾値 ($\theta_i \in [0, 1]$)

$$H(x) = \begin{cases} 0 & (x \geq 0) \\ 1 & (x < 0) \end{cases}$$



減衰関数 $g_i(\tau_i, t) = \begin{cases} \tau & (t - t_i^* \equiv 0 \pmod{3600[s]}) \\ 1 & (\text{otherwise}) \end{cases}$
 $t - t_i^*$: 頂点 i が初めて情報を受信してから経過した時間
初期で情報を受信してから1時間が経過した後は減衰



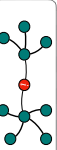
5 実験条件

影響力の高い頂点 総合中心性の高い頂点を含むコンタクト 総合中心性の高いコンタクト

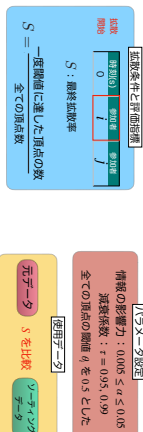
固有ベクトル中心性⁽⁹⁾



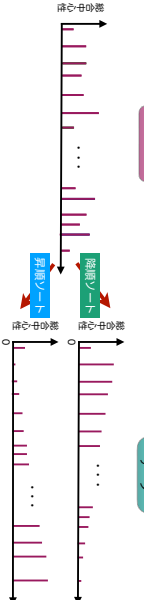
近接中心性⁽¹¹⁾



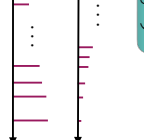
頂点 i の総合中心性 = 固有ベクトル中心性 + 近接中心性



元データ



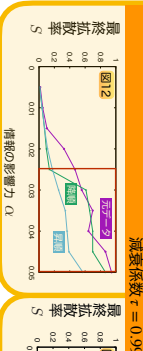
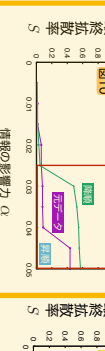
コンタクト



6 実験結果

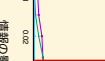
高校

最終拡散率 $\tau = 0.95$



病院

最終拡散率 $\tau = 0.99$



7 まとめ

コンタクトの発生順番が情報拡散率に与える影響について調査した

減衰が強い場合、拡散初期の中心性の高いコンタクトが最終拡散率に大きな影響を与えていることが示された

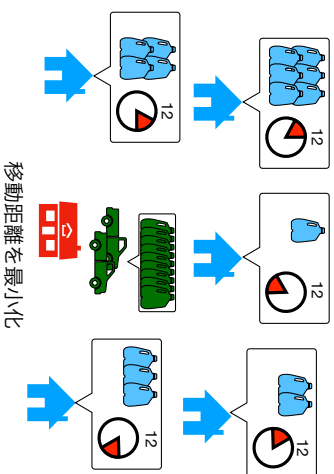
参考文献
[1] D. J. Watts & S. H. Strogatz, *Nature*, **393**, 440-442, 1998.
[2] D. Centola, *Science*, **329**, 1104-1107, 2010.
[3] 石橋, 他, 科学者, **N**, 1-14, 2017.
[4] Y. Tanaka et al., *Proc. of NOLTA*, **2013**, 298-301, 2013.
[5] Y. Tanaka, 他, 科学者, **N**, 1-11, 2020.
[6] <http://www.scicapsystem.org/> (最終閲覧日: 2021.06.29).
[7] P. Vanhatalo et al., *PLoS ONE*, **8**, e71970, 2013.
[8] J. Fontana & A. Banti, *PLoS ONE*, **9**, e107878, 2014.
[9] L. Freeman, *Journal of mathematical sociology*, **2**, 113-120, 1972.
[10] L. Freeman, *Sociometry*, **40**, 35-41, 1977.
[11] A. Bavelas, *The Journal of the acoustical society of America*, **22**, 6, 725-730, 1950.

E13 時間窓付き配送計画問題の構築法と改善法の関係性

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池口研究室
NONLINEAR DYNAMICAL SYSTEM

1. VRPTW



2. 目的関数と制約条件

目的関数

$$\text{minimize} \quad \sum_{k \in V} \sum_{i \in N} \sum_{j \in N} c_{ij} x_{ijk}$$

N : 顧客とデポの集合 ($N = C \cup \{0\}$)

c_{ij} : 頂点*i*から頂点*j*への移動距離

x_{ijk} : 配送車*k*が頂点*i*から頂点*j*に直接向かうかを表す

- ・1: 配送車が頂点*i*から頂点*j*に直接向かう
- ・0: 配送車が頂点*i*から頂点*j*に直接向かわない

制約条件

①全ての顧客を1度だけ訪問する

$$\sum_{k \in V} \sum_{i \in N} x_{ijk} = 1 \quad \forall i \in N$$

③配送車はデポから出発して顧客を訪れ、デポに戻る

$$\sum_{i \in N} \sum_{j \in N} x_{ijk} = 1 \quad \forall k \in V$$

$$\sum_{i \in N} \sum_{j \in N} x_{ijk} = 0 \quad \forall i \in C, \forall k \in V$$

$$\sum_{i \in N} \sum_{j \in N} x_{ijk} = 1 \quad \forall k \in V$$

④それぞれの顧客の指定時刻に配送する

$$q_i \leq s_i \leq b_i \quad \forall i \in N, \forall k \in V$$

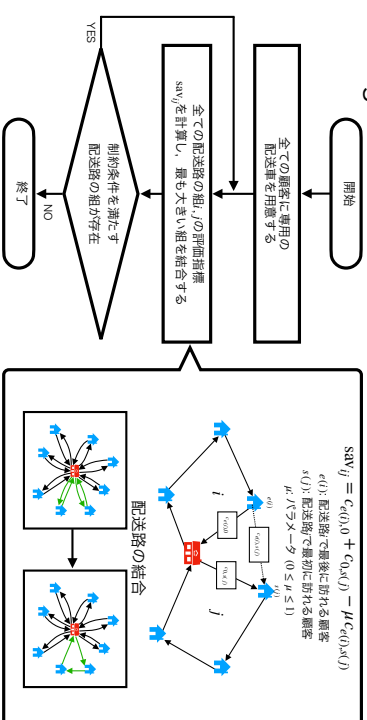
q_i : 配送車が顧客*i*に荷物を届ける時刻

⑤訪問順と配送時刻に矛盾がない

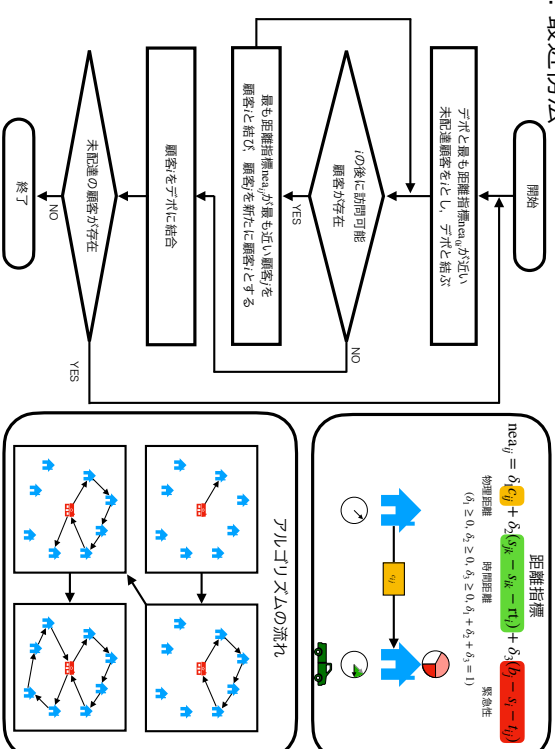
$$s_{ijk} (a_i + t_{ij} - s_{jk}) \leq 0 \quad \forall i, j \in N, \forall k \in V$$

t_{ij} : 頂点*i*から頂点*j*への移動にかかる時間

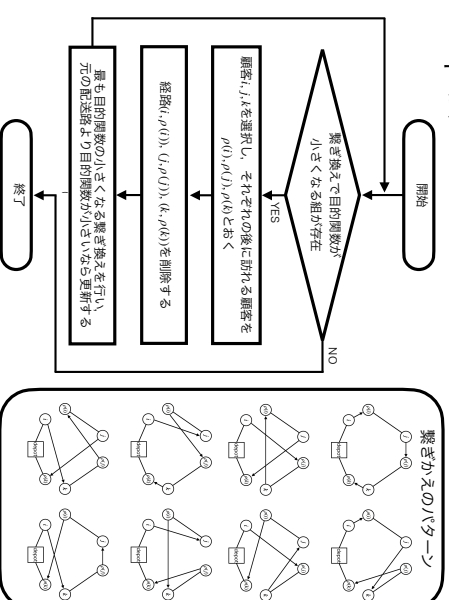
3. Saving Heuristic



4. 最近傍法

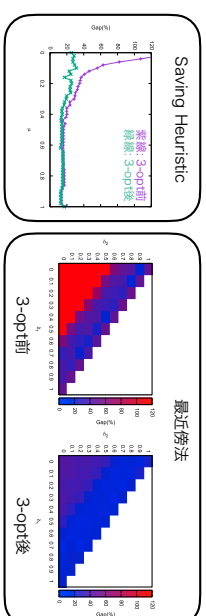


5. 3-opt法



6. 数値実験

それぞれの構築法について、3-opt法実行前と後で誤差率を比較



7. まとめ

- ・VRPTWの構築法と改善法の関係性について調査
- ・巡回セールスマン問題で見られる傾向が確認できた
- ・改善法についてより詳細に調査する予定

参考文献

- [1] D. Borra, "A review of the vehicle routing problem with time windows," *Journal of the Operational Research Society*, vol. 52, no. 2, pp. 248-260, 1997.
- [2] D. Borra, "A review of the vehicle routing problem with time windows," *Journal of the Operational Research Society*, vol. 52, no. 2, pp. 248-260, 1997.

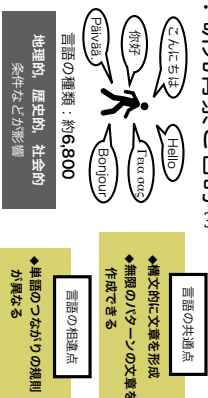
E14

単語の共起を変化させた際の言語ネットワークの構造的特徴の調査

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非線形問題解決軍団
池口研究室
NONLINEAR DYNAMICAL SYSTEM

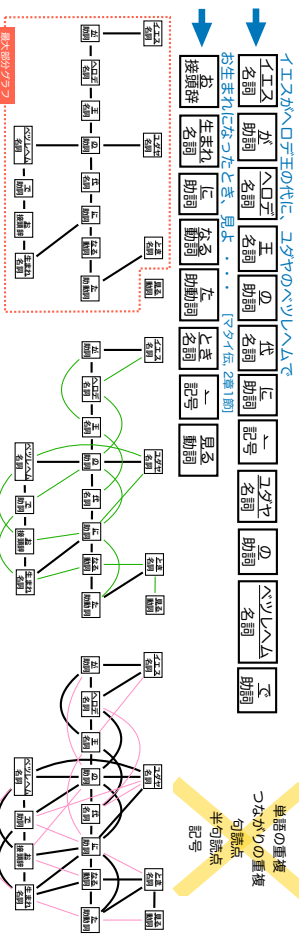
1. 研究背景と目的 ^[1]



2. テキストデータ [2]–[7]

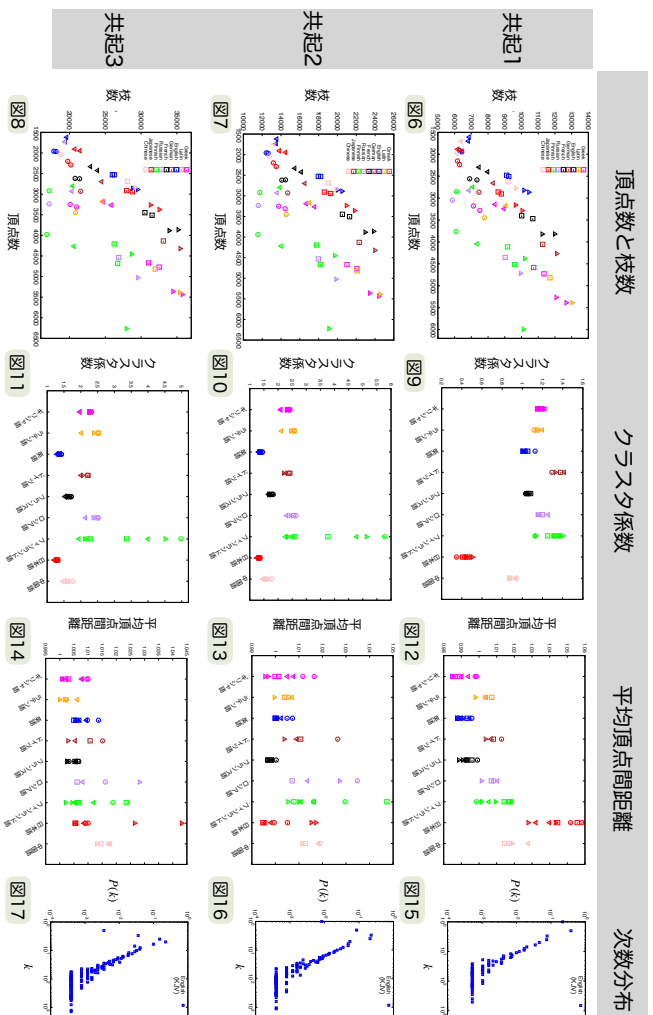
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ラテン語	バチカン	Biblia Sacra Vulgata	201.41.1969
英語	イギリス	King James Version	1611
ドイツ語	ドイツ・オーストリア/旧版	English Standard Version	2001
フランス語	フランス	Lutherbible	1984
ロシア語	ロシア	Loise Segond	1910
ロシア語	ロシア	Second 21	2007
日本語	日本国	Russian Synical Version	1876
中国語	中国	和合本	1954
中国語	中国	Yanhu KefuKongxiantu	1982
中国語	中国	Uasi KefuKongxiantu	1992
中国語	中国	Chinese Synical Bible	2009

3. 言語ネットワーク作成手法



5. 解析結果

□ : ヲタイによる極音響 ○ : ヲルコによる極音響 △ : ルカによる極音響 ▽ : ヲハネによる極音響



4. ネットワーク構造の定量化指標

◆ クラスタ係数 [8]

$$C = \frac{1}{N} \sum_{i=1}^N \frac{2}{k_i(k_i-1)} \sum_{j=1}^N \sum_{i \neq j, l=1}^N a_{ij} a_{jl} \left(\sum_{i \neq j, l=1}^N a_{ij} a_{jl} \right)$$

◆ 平均頂点間距離 [6]

$$L = \frac{1}{E C_2} \sum_{i=1}^N \sum_{j>i}^N d_{ij}$$

図4

◆ 次数分布

$$P(k) = \frac{n_k}{N}$$

◆ 次数分布

図5

N = 頂点数
 E = 枝数
 k_i = 頂点の次数
 a_{ij} = 隣接行列の i, j 成分
 d_{ij} = 頂点 i, j 間の最短距離

6. 7. 8. 9.

7. 今後の課題

参考文献

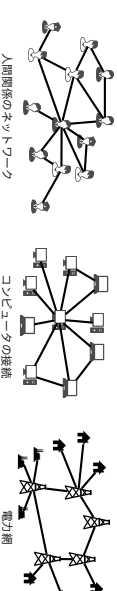
- [1] R. F. C. Canham et al., *Biological Sciences*, **206**, 1482, 2261–2285, 200.
- [2] <https://www.bibsys.org/jsp/jdbc/020.04.13> 閱覽
- [3] <https://www.sciencedirect.com/science/article/pii/S0304416616300466>
- [4] <http://www.cerfacs.fr/020.04.16> 閱覽
- [5] <http://www.eurc1.com/fr/020.04.20> 閱覽
- [6] <https://www.bibsys.org/jsp/jdbc/020.04.26> 閱覽
- [7] <https://www.bibsys.org/jsp/jdbc/020.04.28> 閱覽
- [8] D. J. Watts, et al., *Nature*, **393**, 439–442, 1998.

B12 複雑ネットワークにおける中心性の相関の調査

東京理科大学 池口研究室
B4 石川竜吉

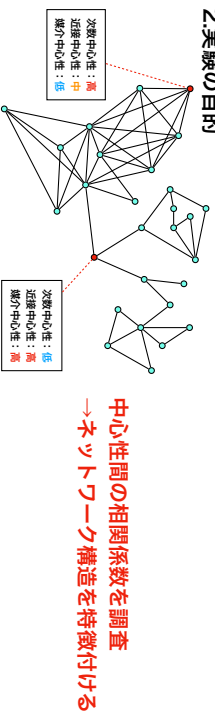


1.背景



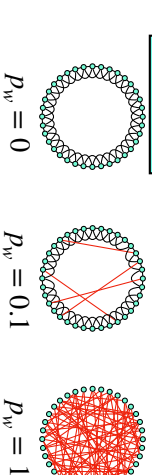
複雑ネットワークでは、相互作用ダイナミクスを定量的に解析可能

2.実験の目的

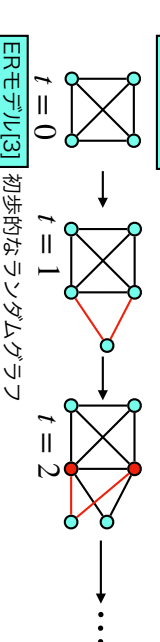


3.ネットワークモデル

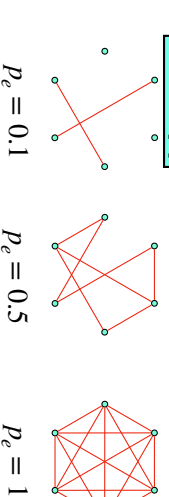
WSモデル[1] スモールワールドネットワークを作成可能



BAモデル[2] 成長・優先的選択により作成

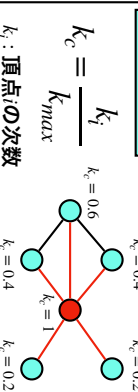


ERモデル[3] 初歩的なランダムグラフ



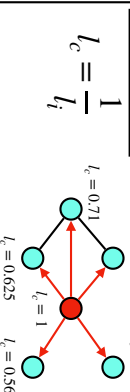
4.中心性

次数中心性[4]



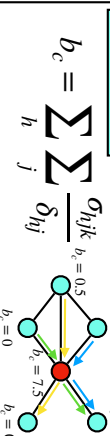
k_i: 頂点の次数

近接中心性[5]



l_i: 頂点の平均最短距離

媒介中心性[6]



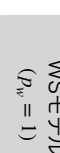
sigma_hjk: 頂点kを通る頂点h, j間の最短経路の数
delta_hj: 頂点h, j間の最短経路の数

5.解析結果

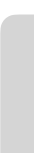
WSモデル (p_w = 0.1)



WSモデル (p_w = 1)



BAモデル



BAモデル (優先的選択なし)



ERモデル



近接中心性: 次数中心性

近接中心性: 媒介中心性

次数中心性: 媒介中心性

ネットワークモデルごとに異なる特徴が得られた

6.まとめ

形状の異なるネットワークに対し、中心性間の相関係数を計算 → それぞれに異なる特徴を得られた。

ネットワーク	次数中心性	近接中心性	媒介中心性
WSモデル (p_w = 0.1)	強い	強い	強い
WSモデル (p_w = 1)	強い	強い	強い
BAモデル	強い	強い	強い
ERモデル	強い	強い	強い

7.今後の課題

今後は言語ネットワークについての研究を行う予定であるため、言語に関する実ネットワークにおいて適用し、解析を行いたい。

参考文献

[1] Barabási, A.-L. & Albert, R. (1999) Emergence of scaling in random networks. *Science*, 286, No. 5427, pp. 509-512.
[2] Albert, R. & Barabási, A.-L. (2002) Statistical mechanics of complex networks. *Journal of Statistical Mechanics*, 2002, No. 01, pp. 01-06.
[3] Watts, D. J. & Strogatz, S. H. (1998) Collective dynamics of 'small-world' networks. *Nature*, 393, No. 6709, pp. 440-442.
[4] Barabási, A.-L. (2009) *Network Science*. Cambridge University Press.
[5] Borgatti, M. P. & Everett, M. G. (2006) Centrality in social networks. *Annual Review of Sociology*, 32, pp. 231-254.
[6] Brandes, U. (2001) A faster algorithm for betweenness centrality. *Journal of Mathematical Sociology*, 25, No. 4, pp. 193-213.

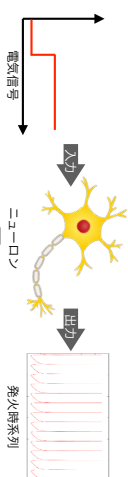
B1 | Izhikevichモデルの外部入力とカオス応答の関係

東京理科大学 池口研究室

B4 塚本陽太

非線形問題解決
池口研究室
NONLINEAR DYNAMICS SYSTEM

1. Izhikevichモデル[1]



ニューロンの発火を再現

Izhikevichモデル

$$\begin{cases} \dot{v} = 0.04v^2 + 5v + 140 - u + I \\ \dot{u} = a(bv - u) \end{cases} \quad (1)$$

$v \geq 30$ で発火とみなし, リセット $\begin{cases} v \leftarrow c \\ u \leftarrow u + d \end{cases}$

v : 膜電位 u : 回復変数 I : 外部入力
パラメータ a, b, c, d によって発火パターンを設定

2. 今回の発表

実験1 入力を一定としたときのカオス応答を調査

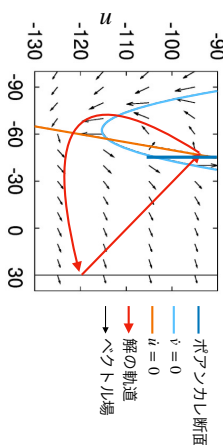
実験2 入力をsin波としたときの応答の調査

3. 相平面

モデルの振る舞いを定性的に調べるための補助

相平面: 横軸に v , 縦軸に u をとった図
ヌルクライン: $\dot{v} = 0, \dot{u} = 0$ の点の集合
 $\begin{cases} u = 0.04v^2 + 5v + 140 + I \\ u = bv \end{cases}$

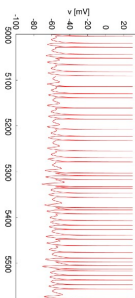
ポアンカレ断面: 直線 $v = c$



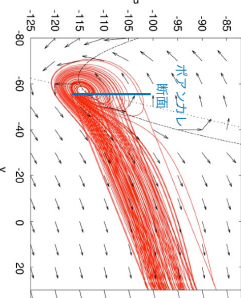
リターンマップ[2]:
ポアンカレ断面上の, 番目の回復変数を u_i とし,
横軸に u_i , 縦軸に u_{i+1} をとったグラフ

4. 入力を一定値としたときのカオスニューロンの応答

カオス応答: 不規則な間隔で発火



カオス応答の相平面の例



ポアンカレ断面上の u_i の値を用いて
リターンマップをプロットする。

実験条件1

カオス応答のパラメータ $(a, b, c, d) = (0.2, 2, -56, -16)$ で固定[3]
入力(一定値) $I(t) = I_{DC}$ (変化範囲 $-104 \leq I_{DC} \leq -90$)

結果1

入力の变化に伴うリターンマップの変化

入力 I の減少に伴い,
形状が連続的に変化
上方に引き伸ばされ, ある値を
超えると下方から出現する

一部の I ではリターンマップが消失しているように見える。
これは, 周期窓と言いい, 応答が周期的になっているためである。

6. まとめと展望

実験1

入力を一定値とするカオス応答では,
リターンマップの変化に規則性が見られる。

リターンマップを関数形で陽に表す

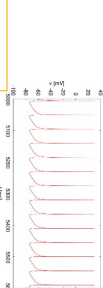
実験2

周期応答のパラメータでも
sin波を与えるとカオス応答になりうる。
sin波を与えるとカオス応答になる理由を
解析的に説明

参考文献

- [1] E. M. Izhikevich, *IEEE Trans. Neural Netw.*, **14**, 1569–1572, 2003.
- [2] 内木はつ, 電子情報通信学会論文誌A, **100**, 195–204, 2017.
- [3] E. M. Izhikevich, *IEEE Trans. Neural Netw.*, **15**, 1063–1070, 2004.
- [4] 杉浦希冠, 2013年度埼玉大学工学部附属システム工学科卒業論文, 2014.

RS(Regular Spiking): 周期的な発火



実験条件2

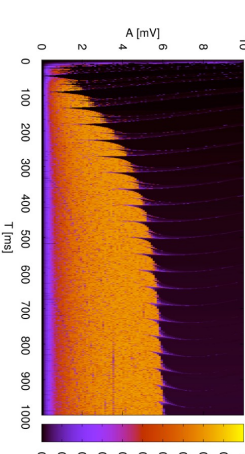
$(a, b, c, d) = (0.02, 0.2, -65, 8)$
外部入力 $I(t) = 10 + A \sin \frac{2\pi}{T} t$
変化範囲 $0 \leq A \leq 10$ (0.1刻み)
 $1 \leq T \leq 1000$ (1刻み)

IS(発火時間間隔)多様度[3]

$R = \frac{I_k}{k}$ I_k : ISの種類数 $R \approx 0$ では周期的
 k : ISの総数 $R \approx 1$ ではカオスの

結果2

振幅 A と周期 T を変えたときの IS 多様度



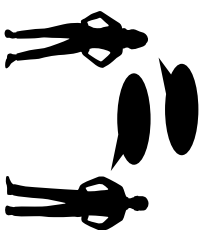
$A > 6$ では $R \approx 0$, つまり周期的
 $A < 6$ では $R \approx 1$, つまりカオスの

非線形WS@オンライン

D14 文章中の単語の出現頻度と言語ネットワークの関係性

東京理科大学 池口研究室
B4 福家水月非線形問題解決
池口研究室
NONLINEAR OPTIMIZATION SYSTEM

1. 研究背景



言語を用いて会話

コミュニケーションのコスト最小化

Zipfの法則[1]

文章中の単語: k
出現回数: $rank(k)$ 出現頻度: $P(k) \approx rank(k)^{-1}$

最大出現回数で正規化

$$P_1(k) = rank(k)^{-1}$$

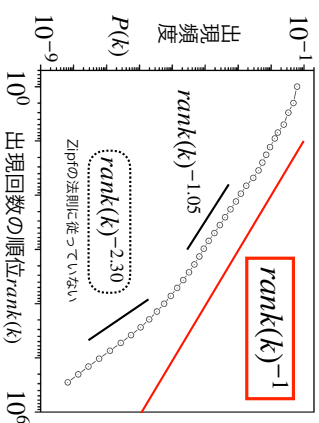
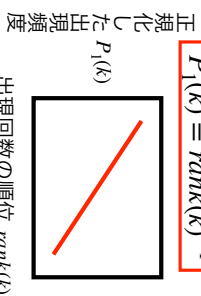


図1: 実際の文章の解析結果(2606冊の英語の書籍)[2]

目的: Zipfの法則を通じて文章の構造に対する理解

2. ネットワーク作成

① 共起関係(前後関係)で枝を繋ぐ

aids | acquire | immune | deficiency | syndrome | be | a | condition
cause | by | a | virus | call | hiv | human | immune | deficiency | virus |

② 枝の重複をなくし、記号を削除

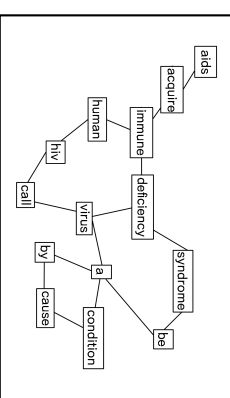
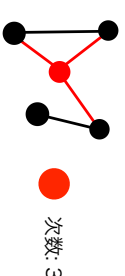


図2: ネットワークの作成手順

3. 次数と次数中心性



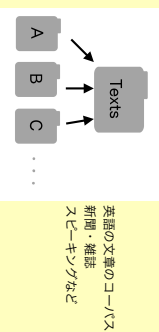
次数中心性

次数

ネットワークの最大次数

4. 解析対象

British National Corpus (BNC)[3]

英語の文章のコーパス
新聞・雑誌
スピーチなど

	Texts	A
単語の種類	376,450	109,505
総単語数	43,143,657	5,813,627

ネットワークに変換

	頂点数	枝数
	109,505	5,508,414

5. 解析結果

① 傾きの変化の境界

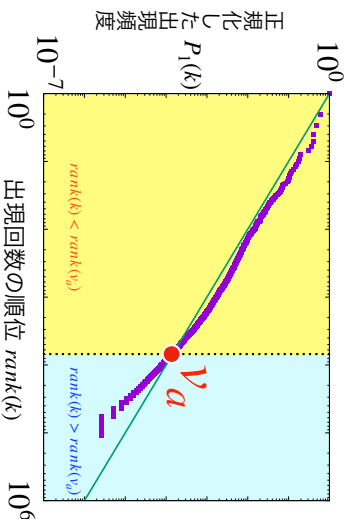


図3: 順位と出現頻度の関係

② 順位と次数の関係性

単語名	$rank(k)$	$P_1(k)$
"devastating"	6,311	1.585×10^{-4}

 $rank(k) < rank(v_a)$

平均次数

平均次数中心性

 $6,310$ 1591.92 2.21×10^{-3} $rank(k) > rank(v_a)$

	頂点数	平均次数	平均次数中心性
	103,194	9.41	0.13×10^{-4}

次数・次数中心性に大きな差

③ 実際の単語

 $rank(k) > rank(v_a)$

- 固有名称 (人名など)
- 数字 (電話番号など)
- 専門的な用語
- 品詞の変化 (動詞+ing → 名詞など)

・汎用性の高い
普通名詞
(coordinator,
campusなど)

6. まとめ

予想 → 結果

Zipfの法則に従わない単語は 日常会話で使う単語も
日常会話で使わない単語が大半 多く確認された

Zipfの法則に従う単語は
文章の作成において最重要

基本的な会話でZipfの法則に従う単語のみで
構成できる可能性?

7. 参考文献

- [1] G. K. Zipf, Human behavior and the principle of least effort, 1949.
- [2] M. A. Montemuro, Physica A, **300**, 567-578, 2001.
- [3] University of Oxford, "The British National Corpus," <http://www.natcorp.ox.ac.uk/>, (最終閲覧日 2021年5月18日)

C12

ワーク付き点過程の時間間隔の差が
Visibility Graphの構造に与える影響の調査

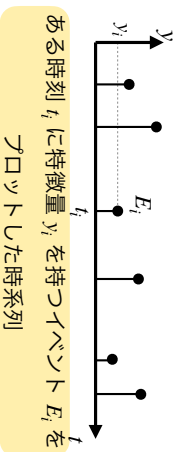
東京理科大学 池口研究室

B4 森 太紀

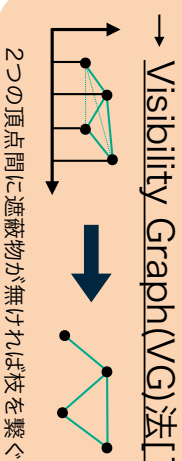
池口研究室
非線形動的力学系
非線形動的力学系

1. 研究背景

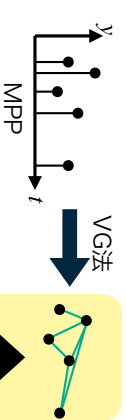
ワーク付き点過程(MPP)とは...



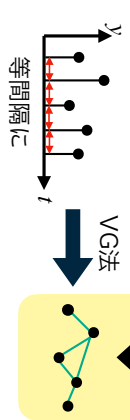
対象時系列 ...
 ・音楽, 生体情報,
 ・地震, 経済指標 など

時系列を複雑ネットワークに変換する手法
→ Visibility Graph(VG)法[1]MPPの場合
イベントの時間間隔を考慮

2. 研究目的



ネットワーク構造の差は？



3. ネットワークの指標

...ネットワークの構造を定量的に測る指標

・クラスタ係数 $C \dots$ の構造の割合

$$C = \frac{1}{n} \sum_{c=1}^n c_i, \quad c_i = \frac{\text{頂点}i\text{を含む三角形の数}}{k_i C_2}$$

※ k_i は頂点 i に繋がる枝数

・平均頂点間距離 $L \dots$ 各頂点間の最短距離の平均

$$L = \frac{1}{n C_2} \sum_{i,j=1, i \neq j}^n d_{i,j}$$

※ $d_{i,j}$ は頂点 i, j 間の最短距離

4. 実験条件・使用した時系列

(i) Lorenz方程式

$$\begin{cases} \frac{dx}{dt} = -\sigma x + \sigma y \\ \frac{dy}{dt} = -x z + r x - y \\ \frac{dz}{dt} = x y - b z \end{cases}$$

$\sigma = 10, r = 28, b = \frac{8}{3}$

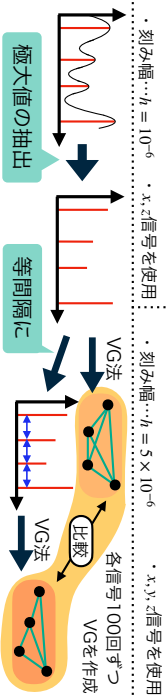
(ii) Chua回路 (無次元化状態)[2]

$$\begin{cases} \frac{dx}{dt} = k\alpha(y - x - f(x)) \\ \frac{dy}{dt} = k(x - y + z) \\ \frac{dz}{dt} = k(-\beta y - \gamma z) \end{cases}$$

$k = 1$
 $\alpha = 9.352$
 $\beta = 14.790$
 $\gamma = 0.016$
 $m_0 = -1.138$
 $m_1 = -0.722$

$$f(x) = bx + \frac{1}{2} (m_0 - m_1) (|x + 1| - |x - 1|)$$

・初期値の範囲... x, y, z 全て(0,201)
 ・対象時間... $10 \leq t \leq 2010$



・初期値の範囲... x, y, z 全て(0,0.61)
 ・対象時間... $10 \leq t \leq 5010$



5. 実験結果

*ETS...Equally sampled Time Series (等間隔サンプリング時系列)
 *クラスタ係数 C と平均頂点間距離 L は次数保存ランダムネットワークで正規化した。

信号	時間間隔の分散	頂点数	C_{MPP}	C_{ETS}	L_{MPP}	L_{ETS}	MPP 枝数	ETS 枝数	追加された枝数	削除された枝数
Lorenz x	0.099	2090.72	141.46	140.28	1.58	1.57	7270.36	7306.11	84.45	48.70
Lorenz z	0.010	2663.10	171.47	172.91	1.32	1.32	8876.72	8916.29	50.37	10.80
Chua x	0.356	2096.67	194.29	192.71	1.45	1.45	5672.25	5708.42	60.29	24.12
Chua y	0.065	2367.47	181.99	180.79	1.45	1.45	5903.30	5925.05	50.56	28.81
Chua z	0.084	2278.63	196.04	197.10	1.48	1.48	6657.72	6651.27	24.79	31.24

MPPの時間間隔の分散の大きさに関わらず、VGの構造に大きな変化はなかった

6. まとめ

MPPとその時間間隔を無視した場合のVGの構造差を確認。
 -Chua回路, Lorenz方程式では
 2つのVGの構造に大きな差は見られなかった。

今後の方針

・他の力学系や実データで
 VGの構造差が見られるか確認。
 ・どのような時系列の場合に
 構造差が現れるか検討

参考文献

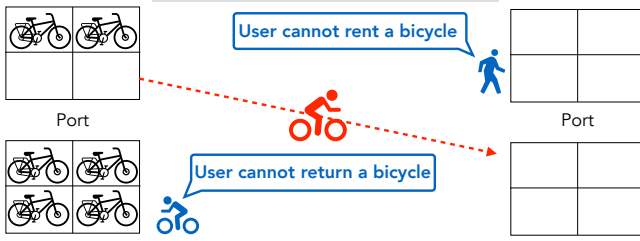
- [1] L. Lacasa, et al., PNAS, 105, 4972–4975, 2008
 [2] L. O. Chua, et al., IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, 40, 732–744, 1993

Statistical analysis on usage history of bike sharing systems

Honami Tsushima

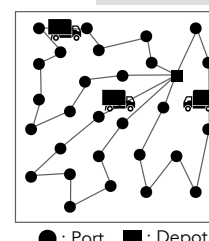
Ikeguchi laboratory, Tokyo University of Science

1. Bike Sharing System (BSS)



Feature	User can rent a bicycle at a port, use it for a short trip and return it to a different port
Issue	The number of bicycles at each port unbalanced
Solution	Capacitated vehicles need to relocate bicycles among ports

2. Previous Study and Aim of Study



Previous study
We have already proposed a method for finding optimal tours of vehicles in reasonable time frames [1,2]

We used original benchmark instances with randomly placed ports

Need to building realistic instances

Aim of study

We analyze usage history of bike sharing systems

Q1. Are excesses and lacks of bicycles generated ?

Q2. What are the bicycles rented and return patterns?

3. Analysis of Usage History of BSSs

Data

City	Boston	Washington D.C.	New York	Chicago
Name	Blue Bikes [5]	Capital Bikeshare [6]	Citi Bike [4]	Divvy [3]

We used August data

Are excesses and lacks of bicycles generated ?

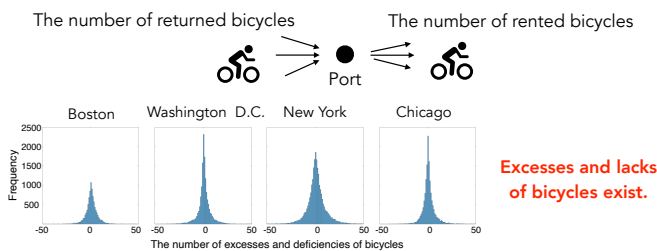


Fig.1. Difference between the number of rented and returned bicycles on a day

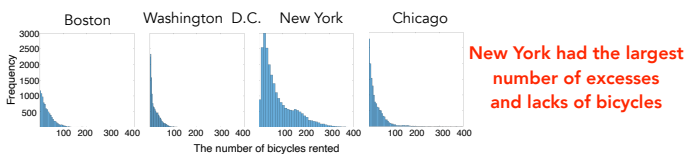


Fig.2 The number of bicycles rented in a day

What are the bicycles rented and returned patterns?

Raster plot

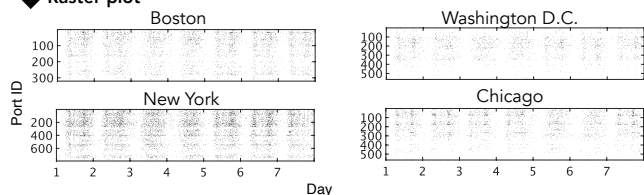


Fig.3 Raster plots of bicycles rented timing for the four BSSs

We treat the bicycle rental and return timings data as a point process

Inter-venet-intervals (IEIs)

Timing of a bicycle is rented

$$T_i = t_{i+1} - t_i$$

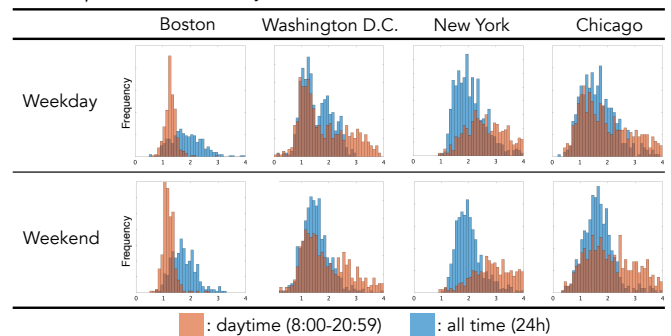
Time (min)

◆ Coefficient variation (C_V) measures the global variability of all IEIs

$$C_V = \frac{\sqrt{\frac{1}{n-1} \sum_{i=1}^n (T_i - \bar{T})^2}}{\bar{T}}$$

$C_V = 0$	Regular	$\bar{T}$: The mean of IEIs
$C_V = 1$	Poisson process	n : The number of IEIs

Tab. 1 C_V values of rented bicycles



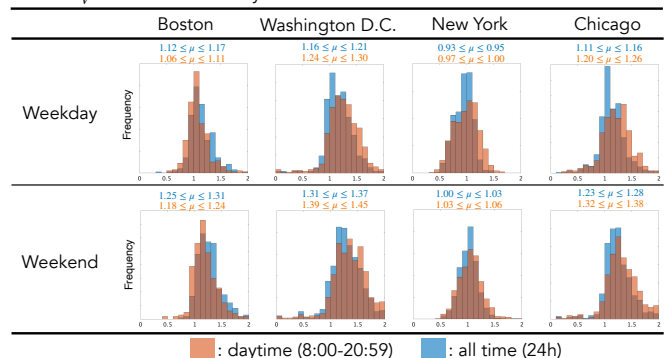
The highest frequent values of C_V are larger than unity except for daytime in Boston

◆ Local variation (L_V) measures the local variability of all IEIs [7,8]

$$L_V = \frac{1}{(n-1)} \sum_{i=1}^{n-1} \frac{3(T_i - T_{i+1})^2}{(T_i + T_{i+1})^2}$$

$L_V = 0$	Regular
$L_V = 1$	Poisson process

Tab. 2 L_V values of rented bicycles



The highest frequency values of L_V were close to unity for all BSSs
We estimated 95% confidence intervals μ did not contain unity

4. Conclusion

A1. Excesses and lacks of bicycles exist. However, there was no significant difference in the number of excesses and lacks of bicycles among the four BSSs.

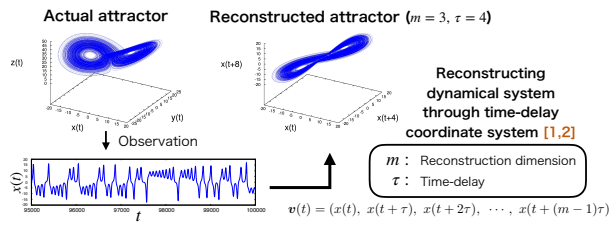
A2. The temporal patterns of events of rented and returned bicycles among the four BSSs were the same (weekdays and weekends, and daytime and all day). These temporal patterns did not necessarily follow Poisson process.

- References [1] H. Tsushima, et al., *Journal of Signal Processing*, 11(4), pp.157-160, 2018. [2] H. Tsushima, et al., *Applied Sciences*, 11(16), 7749, 2021. [3] Divvy Bikes. <https://www.divvybikes.com/system-data>. [4] Citi Bike. <https://www.citibikenyc.com/system-data>. [5] BLUE bikes. <https://www.bluebikes.com/system-data>. [6] Capital Bikeshare. <https://www.capitalbikeshare.com/system-data>. [7] S. Shinomoto, et al., *Neural Computation*, 15(12), pp. 2823-2842, 2003. [8] S. Shinomoto, et al., *Biosystems*, 79(1-3), pp. 67-72, 2005.

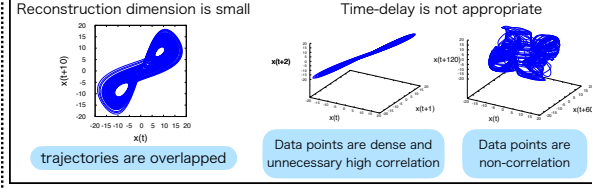
Relationship between similarities of inter-point distance distributions on attractors and reconstruction parameters

Kazuya Sawada
Ikeguchi laboratory, Tokyo University of Science

1. Introduction



Motivation



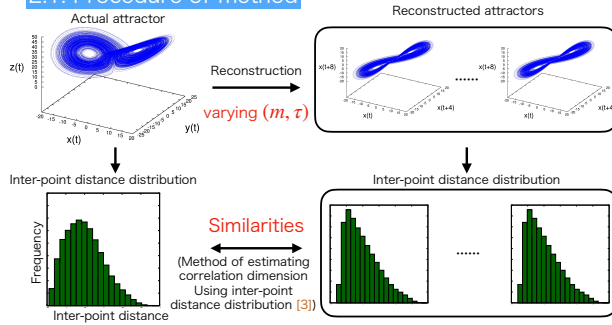
Purpose

To reveal geometric characteristics of attractors when varying reconstruction dimension and time-delay

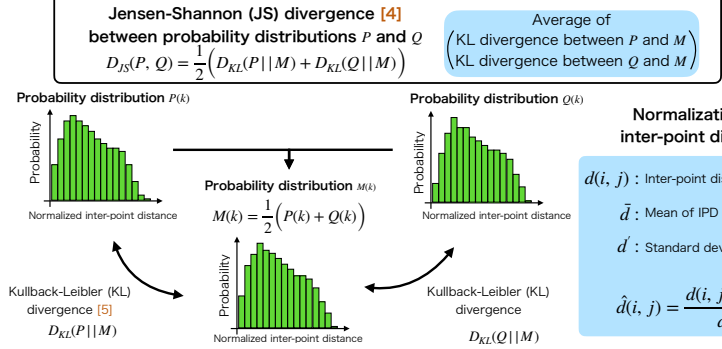
Selecting appropriate reconstruction parameters is important

2. Methods

2.1. Procedure of method



2.2. Dissimilarity between probability distributions



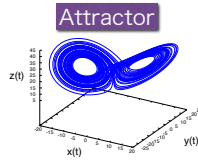
3. Dynamical systems and experimental settings

We use four types of nonlinear dynamical system

• Lorenz system [6]

$$\begin{cases} \dot{x} = \sigma(-x + y) \\ \dot{y} = -xz + rx - y \\ \dot{z} = xy - wz \end{cases}$$

$$\sigma = 10, r = 28, w = 8/3$$

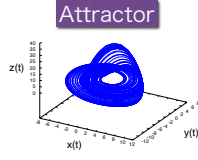


Data length: 5,000
Step size: 0.01
Sampling rate: 0.01

• Rössler system [7]

$$\begin{cases} \dot{x} = -y - z \\ \dot{y} = x + ay \\ \dot{z} = b + z(x - c) \end{cases}$$

$$a = 0.36, b = 0.4, c = 4.5$$

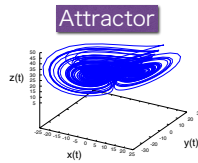


Data length: 10,000
Step size: 0.01
Sampling rate: 0.05

• Chen system [8]

$$\begin{cases} \dot{x} = p(-x + y) \\ \dot{y} = (s - p)x - xz + sy \\ \dot{z} = xy - qz \end{cases}$$

$$p = 35, q = 3, s = 28$$

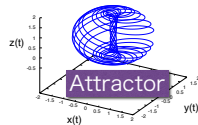


Data length: 5,000
Step size: 0.01
Sampling rate: 0.01

• Langford system [9]

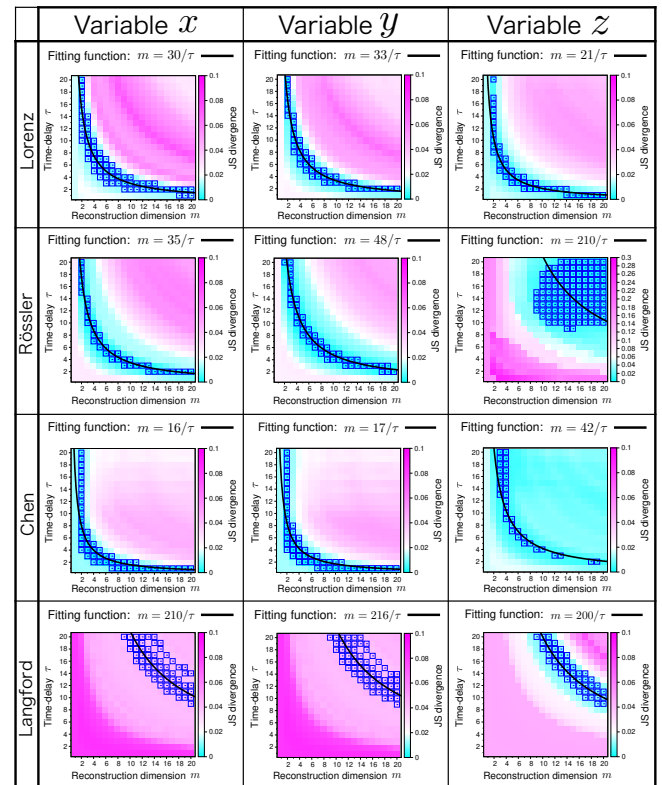
$$\begin{cases} \dot{x} = (z - \beta)x - \omega y \\ \dot{y} = \omega x + (z - \beta)y \\ \dot{z} = \lambda + \alpha z - \frac{1}{3}z^3 - (x^2 + y^2)(1.0 + \rho z) + \varepsilon z x^3 \end{cases}$$

$$\alpha = 1, \beta = 0.7, \lambda = 0.6, \omega = 3.5, \rho = 0.25, \varepsilon = 0$$



Data length: 5,000
Step size: 0.01
Sampling rate: 0.01

4. Results



JS divergence is minimized (=geometric characteristic is maximized) when the product of the reconstruction dimension and time-delay keep a small constant value

5. Conclusion

We evaluated the similarities between IPDDs on actual and reconstructed attractors when varying reconstruction parameters.

It is important to keep the embedding window constant.

These results quantitatively demonstrate the importance of keeping the embedding window ($m \cdot \tau$) constant, which was mentioned in previous studies [e.g. 10, 11].

Reference

- [1] F. Takens., *Dynamical System and Turbulence*, **898**, 366–381, 1981.
- [2] T. Sauer, et. al., *J. Stat. Phys.*, **65**, 3,579–616, 1991.
- [3] P. Grassberger et. al., *Phys. Rev. Lett.*, **50**, 5, 346–349, 1983.
- [4] J. Lin, *IEEE Trans. Inf. Theory*, **37**, 1, 145–151, 1991.
- [5] S. Kullback, et. al., *Ann. math. stat.*, **22**, 1, 79–86, 1951.
- [6] E. N. Lorenz, *J. Atmos. Sci.*, **20**, 2, 130–141, 1963.
- [7] O. E. Rössler, *Phys. Lett. A*, **57**, 5, 397–398, 1976.
- [8] G. Chen, et. al., *Int. J. Bifurcat. Chaos*, **9**, 7, 1465–1466, 1999.
- [9] W. F. Langford, *Numerical Methods for Bifurcation Problems*, **70**, 285–295, 1984.
- [10] H. S. Kim et. al., *Phys. Rev. E*, **58**, 5, 5676–5682, 1998.
- [11] M. Small et. al., *Physica D*, **194**, 3–4, 283–296, 2004.

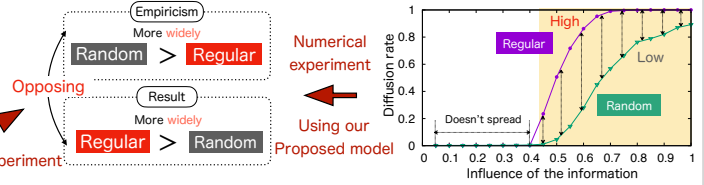
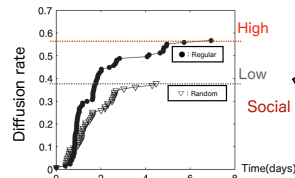
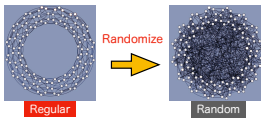
Analysis of the influence of contact order on information diffusion by surrogate temporal networks

Tokyo University of Science
Ikeguchi Lab M2 Luyan Xu

1 Background

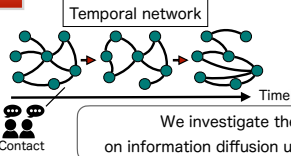
Many research on information diffusion for networks have been reported.
D. Centola, *Science*, **329**, 1194–1197, 2010.

E.g.



The result by our model supports the result of Centola's social experiment. However, our investigations were all on the static networks

2 Purpose of our study



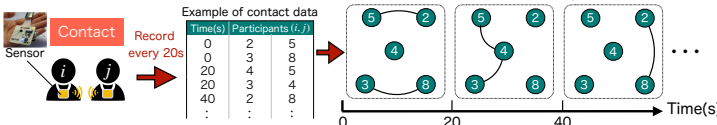
Purpose

To reveal the influence of dynamic structure of temporal networks on information diffusion

We investigate the influence of the contact order on information diffusion using the contact data in the real world

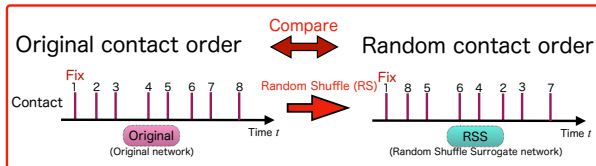
3 Contact data & Temporal network

- (1) Data from a high school (The number of participants: 126, Duration: 3 days)
- (2) Data from a hospital (The number of participants: 75, Duration: 4 days)



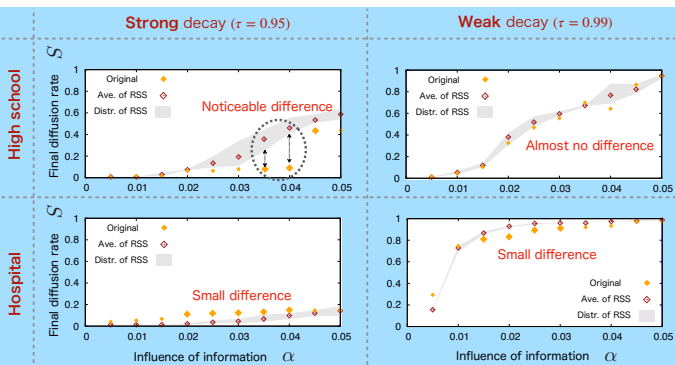
5 Numerical experiments

How does the contact order in the real world affect the information diffusion?



Final diffusion rate $S = \frac{\text{The number of vertices once reached thresholds}}{\text{The number of all vertices}}$

Start the diffusion from
Time(s) | Participants (i, j)
0 | i* | j



The contact order in the real world affects the information diffusion (Especially, when the decay of interest is strong)

6 Conclusion

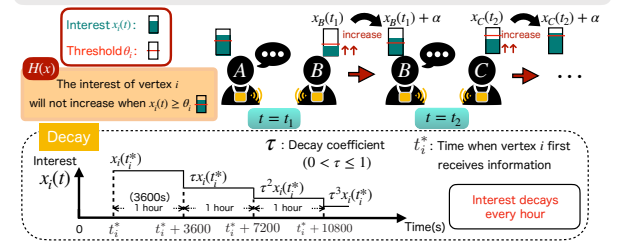
We investigated the influence of contact order on information diffusion

	Strong decay	Weak decay
Contact order	Tend to have a Strong influence	Weak influence
Contacts with high centralities	Important for Spreading information	Not important for Spreading information

4 Proposed model of information diffusion

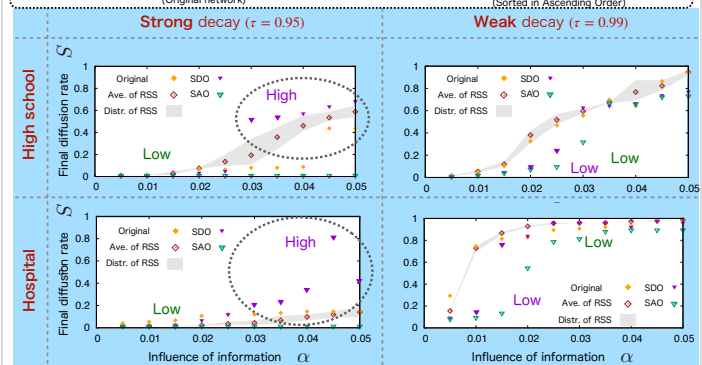
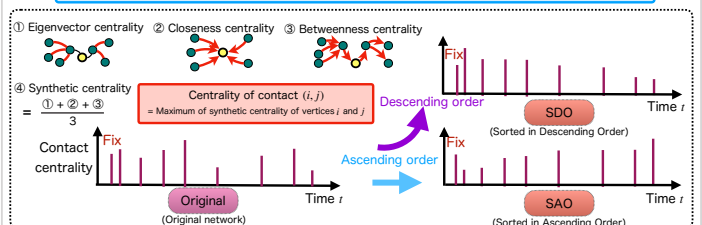
$$x_i(t+20) = g_i(\tau, t) x_i(t) + \alpha H(x_i(t) - \theta_i) \sum_{j \in G_i(t)} F(x_j(t) - \theta_j)$$

α : Influence of information $F(x)$: Step function $G_i(t)$: Set of adjacent vertices of vertex i at time t



Information spread more widely → The keys are contacts with important people? = The vertices with high centralities

How do the contacts with high centralities affect information diffusion?
Ascending order of contact centrality → Compare → Random contact order → Compare → Descending order of contact centrality



If the decay of interest is strong, Contacts with high centralities are Important for spreading information in the early term of diffusion

If the decay of interest is weak, contacts with high centralities are Not important for spreading information

References

- [1] D. J. Watts and S. H. Strogatz, *Nature*, **393**, 440–442, 1998.
- [2] D. Centola, *Science*, **329**, 1194–1197, 2010.
- [3] <http://www.sociopatterns.org/> (Access: 2021/11/09).
- [4] J. Fournet and A. Barrat, *PLOS ONE*, **9**, e107878, 2014.
- [5] P. Vanhems et al., *PLOS ONE*, **8**, e73970, 2013.
- [6] P. Bonacich, *Journal of Mathematical Sociology*, **2**, 1, 113–120, 1972.
- [7] A. Bavelas, *The Journal of the Acoustical Society of America*, **22**, 725–730, 1950.
- [8] G. Sabidussi, *Psychometrika*, **31**, 4, 581–603, 1966.
- [9] L. Freeman, *Sociometry*, **40**, 1, 35–41, 1977.
- [P1] L. Xu et al., *Technical report of IECE*, **120**, 55, NLP2020-15, 23–26, 2020.
- [P2] L. Xu et al., *IEICE Conf.*, N-1-11, 2020.
- [P3] L. Xu et al., *NCSP'21*, 73–76, 2021.
- [P4] L. Xu et al., *IEICE Gen. Conf.*, N-1-6, 2021.
- [P5] L. Xu et al., *The 2021 Nonlinear Science Workshop*, 2021.

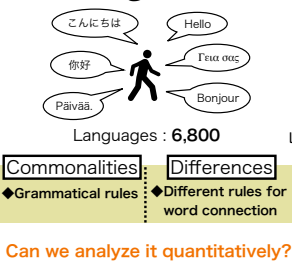
Publications

Investigation of Structural Features of Word Co-occurrence Networks with Varying Numbers of Connected Words

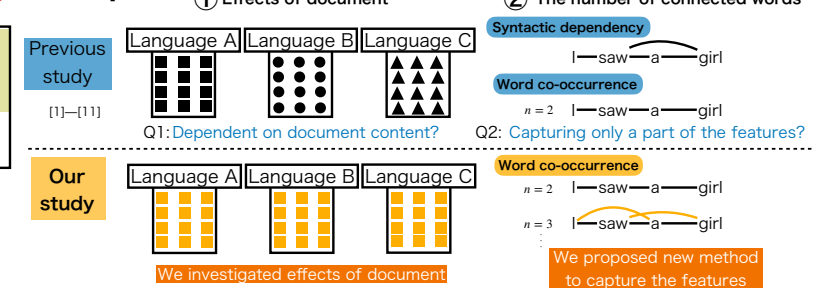
Ikeguchi Laboratory M2, Tokyo University of Science, Kihei Magishi



1. Background



2. Purpose



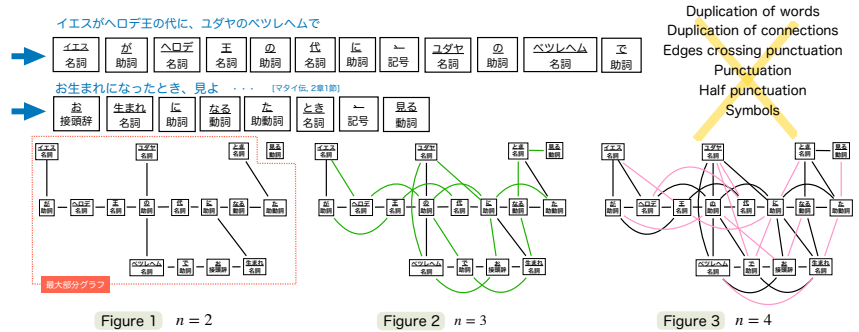
3. Text data

- (i) New Testament (ii) United Nations
(iii) Paris Agreement (iv) Novel

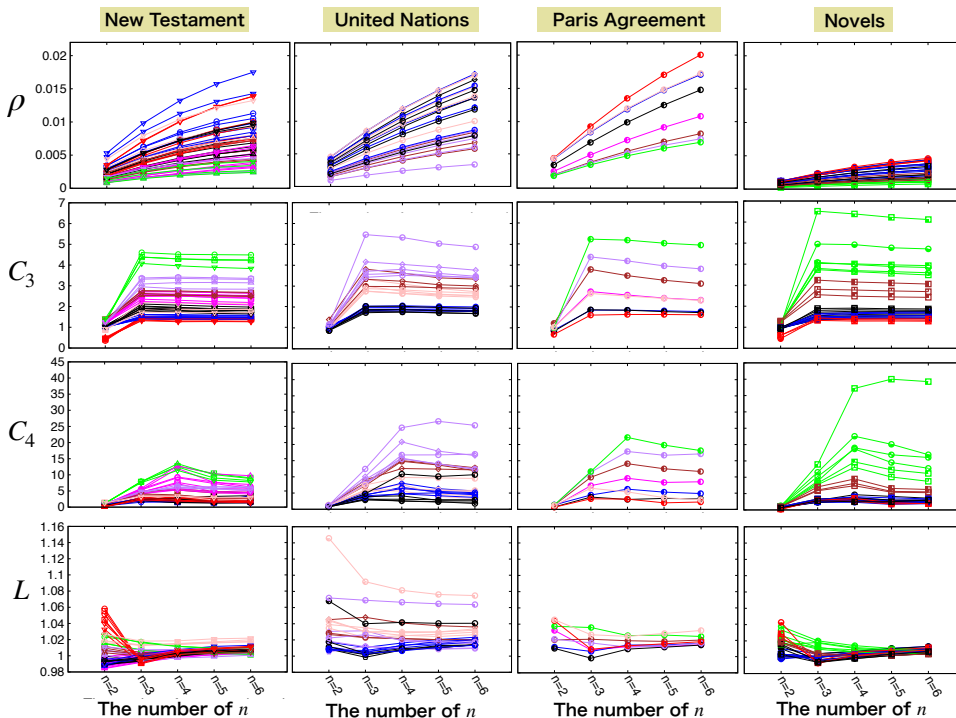
Language family	Language	Greek	English	German	French	Russian	Finnish	Japanese	Chinese
(i)	Matthew								
	Mark								
	Luke								
	John								
	IMP(2011)								
	IMP(2016)								
	IMP(2018)								
	POL(07)								
	POL(10)								
	REPC								
(ii)	The Baskervilles								
	The Pictures of Dorian Gray								
	Gulliver's Travels								
	La Mer								
	The Adventure of Tom Sawyer								
	Treasure Island								
	The Windmill								
	A Christmas Carol								

●: Two documents ○: One document ×: No documents

4. Word co-occurrence network



5. Results and discussion

Figure 4 Each network measure when n increases.The number of n

The increasing rate of Japanese and Finnish is high

➔ Possibility of capturing the features of case marker

Network measure

Density

$$\rho = \frac{E}{N \cdot C_2}$$

Clustering coefficient

$$C_3(i) = \frac{2}{k_i(k_i - 1)} \sum_{j=1}^{k_i} \sum_{l=1}^{k_i} a_{ij} a_{il}$$

Square clustering coefficient

$$C_4(i) = \frac{\sum_{j=1}^{k_i} \sum_{l=1}^{k_i} \sum_{m=1}^{k_i} a_{ij} a_{il} a_{im}}{\sum_{j=1}^{k_i} \sum_{l=1}^{k_i} a_{ij} a_{il}}$$

Average shortest-path length

$$L(i) = \frac{1}{k_i} \sum_{j=1}^{k_i} d_{ij}$$

N = The number of vertices
 E = The number of edges
 k_i = Degrees of vertex i
 a_{ij} = i, j components of adjacent matrix
 n_k = The number of vertices which have k degrees
 d_{ij} = Shortest-path between vertex i, j
 v_j = Vertex which adjacent to vertex i
 ϕ_{ij} = The number of square using vertex i, v_j, v_j
 ϕ_{ij} = $1 + \phi_{ij} + \phi_{ij}$
 ϕ_{ij} = If vertices v_j, v_j are connected 1, otherwise 0

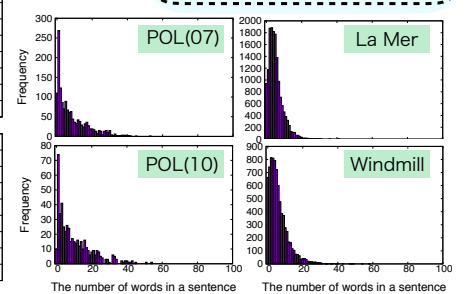


Figure 5 Frequency distribution of the number of words in one sentence.

Document content affects structural features of word co-occurrence network

The amount of text also may affect

6. Conclusion

① Effects of document

Document content affects word co-occurrence network.

The amount of text is also important.

② The number of connected words

Proposed method is a promising approach

References

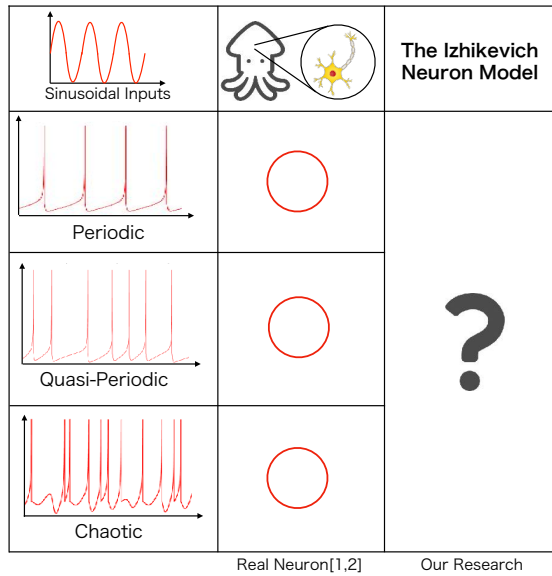
- [1] D. R. Amancio et al., *New Journal of Physics*, **13**, 12, 123024, 2011.
 [2] D. R. Amancio et al., *New Journal of Physics*, **14**, 4, 043029, 2012.
 [3] D. R. Amancio et al., *Physica A*, **391**, 16, 4406–4419, 2012.
 [4] D. R. Amancio et al., *Journal of Statistical Mechanics*, **2015**, 3, P03005, 2015.
 [5] D. R. Amancio et al., *Physica A*, **391**, 4, 1855–1864, 2012.
 [6] O. Altman et al., *Journal of Quantitative Linguistics*, **18**, 4, 291–336, 2011.
 [7] L. Wei et al., *Physica A*, **388**, 23, 6001–6009, 2009.
 [8] G. Yang et al., *Physica A*, **393**, 579–589, 2014.
 [9] Y. Shimada et al., *Complexity*, **127**, 5, 56003, 2019.
 [10] D. R. Amancio et al., *PLoS One*, **8**, 7, e67310, 2013.
 [11] R. F. J. Cancho et al., *Physical Review E*, **69**, 5, 056115, 2004.
 [12] https://www.bible.com (2020-03-24)
 [13] http://www.corbano.org (2020-04-10)
 [14] http://www.ancient.com (2020-04-20)
 [15] https://www.biblegateway.com (2020-04-20)
 [16] https://www.bible.com (2020-04-28)
 [17] http://www.aonora.org
 [18] http://www.gutenberg.org
 [19] https://documents.un.org (2021-06-16)
 [20] https://eur-lex.europa.eu (2021-06-23)
 [21] https://www.mofa.go.jp (2021-06-23)
 [22] https://unfccc.int/press-and-meetings/the-paris-agreement (2021-06-23)
 [23] http://ukip.org.uk/high-impact-research (2020-01-08)
 [24] https://www.cis-uni-muenchen.de/~schmid/tools/TreeTagger (2020-04-27)
 [25] https://www.cis-uni-muenchen.de/~schmid/tools/TreeTagger (2021-07-21)
 [26] L. C. Freeman, *Social Networks*, **1**, 3, 215–239, 1978.
 [27] A. Barabási, *The Journal of the American Statistical Association*, **1**, 3, 215–239, 1978.
 [28] D. J. Watts et al., *Nature*, **393**, 6684, 440–442, 1998.
 [29] P. G. Lind et al., *Physical Review E*, **72**, 5, 056127, 2005.
 [30] 藤原新平, *科学技術*, **119**, 471, 77–82, 2020.
 [31] 藤原新平, *科学技術*, **120**, 55, 27–32, 2020.
 [32] K. Magishi et al., *NSCF21*, **1**, 42–48, 2021.
 [33] 藤原新平, *科学技術*, **121**, 1–21, 2021.
 [34] 藤原新平, *科学技術*, **121**, 1–21, 2021.
 [35] K. Magishi et al., *Nonlinear Theory and Its Applications, IEICE*, **2021** (投稿中).

Non-Periodic Responses of the Izhikevich Neuron Model to Periodic Inputs

Tokyo University of Science Yota Tsukamoto



1. Introduction



2. The Izhikevich Neuron Model[3]

$$\begin{cases} \dot{v} = 0.04v^2 + 5v + 140 - u + I & \text{When } v \geq 30, \\ \dot{u} = a(bv - u) & v < c \text{ and } u \leftarrow u + d \end{cases} \quad (1) \quad (2)$$

v : Membrane potential u : Recovery variable I : Input current

$$\text{Input: } I(t) = I_{DC} + I_{AC} = 10 + A \sin \frac{2\pi}{T} t \quad (3)$$

Parameters : $a = 0.02, b = 0.2, c = -65, d = 8$ (Regular Spiking)

3. Trajectories

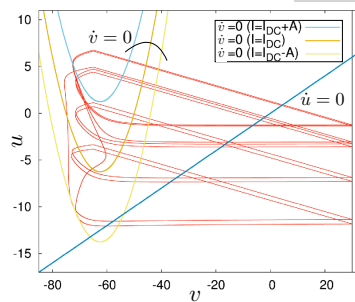


Fig. 1. A Periodic Response ($A = 7.5, T = 200$)

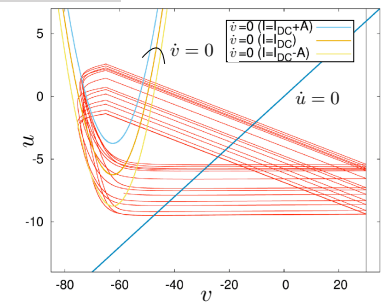
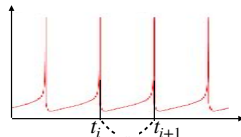


Fig. 2. An Irregular Response ($A = 2.5, T = 200$)

3. The Diversity Index of Inter-Spike Intervals[4]

Inter-Spike Interval (ISI)

$$s_i = t_{i+1} - t_i \quad (4)$$



Diversity Index of ISIs[4]

$$R = \frac{M}{N} \quad (5) \quad \begin{matrix} M : \text{Number of different types of ISIs} \\ N : \text{Total number of ISIs} \end{matrix}$$

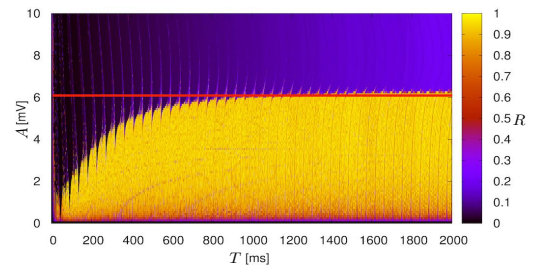
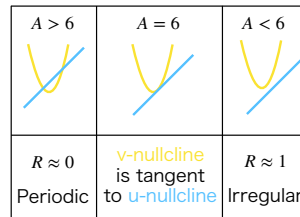
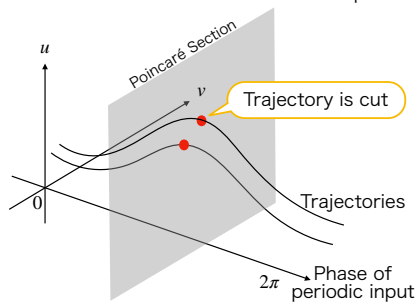


Fig. 3. The Diversity Indices of ISIs when the amplitude A and period T are changed

4. Stroboscopic Plots

A method to observe state points at certain phase of periodic input[5-7]



	Distinct Points	Closed Curve
Poincaré Section		
Attractor	Limit Cycle	Torus
Response	Periodic	Quasi-Periodic

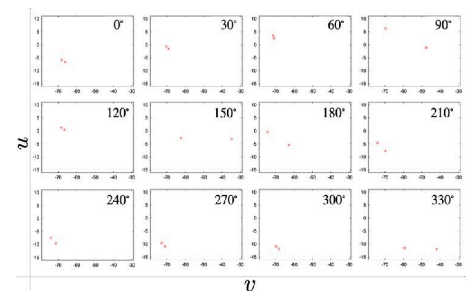


Fig. 4. A Periodic Response ($A = 7.5, T = 200$)

5. Summary

	Real Neuron	Model
Periodic		
Quasi-Periodic		
Chaotic		Not Found

References

- [1] H. Hayashi et al., *Phys. Lett. A*, **88**, 435–438, 1982.
- [2] K. Aihara et al., *Phys. Lett. A*, **116**, 313–317, 1986.
- [3] E. M. Izhikevich, *IEEE Trans. Neural Netw.*, **14**, 1569–1572, 2003.
- [4] N. Sugiura et al., *IEICE Tech. Rep.*, NLP2013-34, 2013.
- [5] H. Hayashi et al., *PLA*, **88**, 435–438, 1982.
- [6] K. Aihara et al., *PLA*, **116**, 313–317, 1986.
- [7] K. Aihara et al., *JTB*, **109**, 249–269, 1984.

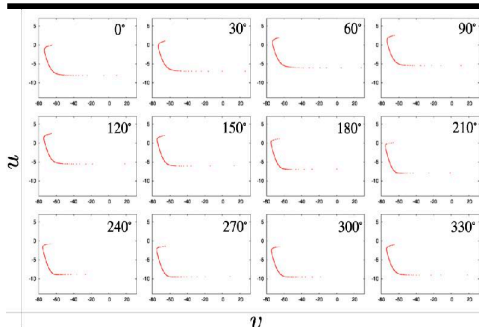


Fig. 5. An Irregular Response ($A = 2.5, T = 200$)

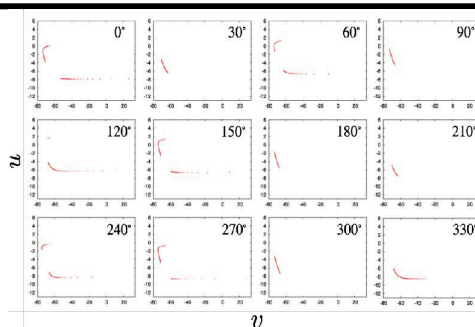


Fig. 6. An Irregular Response ($A = 1.5, T = 180$)

多義語ネットワークを用いた感情の分析

東京理科大学 池口研究室 B4 福家水月



1. 背景

感情の先行研究

C.Darwin [1]
7つの基本的感情
進化生物学

P.Ekman [2]
5つの基本的感情
心理学

感情を表現する言語

①“дурной”: Russian
意味: “BAD”・“UGLY”

異なる複数の感情を意味する多義語

②“mauvais”: French
意味: “BAD”・“SEVERE”

感情と別の概念を意味する多義語

仮説

言語における感情と他分野における感情は違う？

手法

概念同士のつながりを明示できるネットワーク

多義語ネットワークを用いた
言語における基本的感情の調査

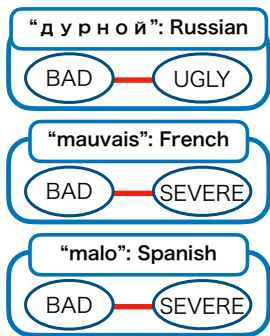
2. 解析対象

CLICS³ [3]

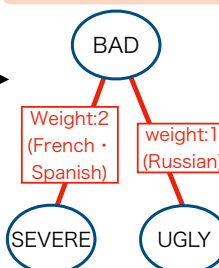
- ・様々な語族・言語の単語と単語の意味を収録
- ・現在使われていない言語も収録
- ・同じ語形・意味を多義語と定義

単語数	言語数
1,425,418	3,061

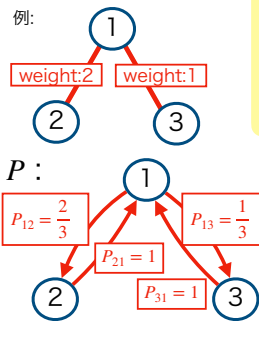
3. ネットワーク作成 [4]



重み付きネットワーク化
重みは言語の数



ランダムウォーク



$$P_{ij} = \frac{A_{ij}}{\sum_j A_{ij}}$$

A : 隣接行列
P : 遷移確率行列

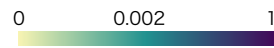
ランダムウォークを繰り返し行った
ネットワーク

感情の頂点を抽出

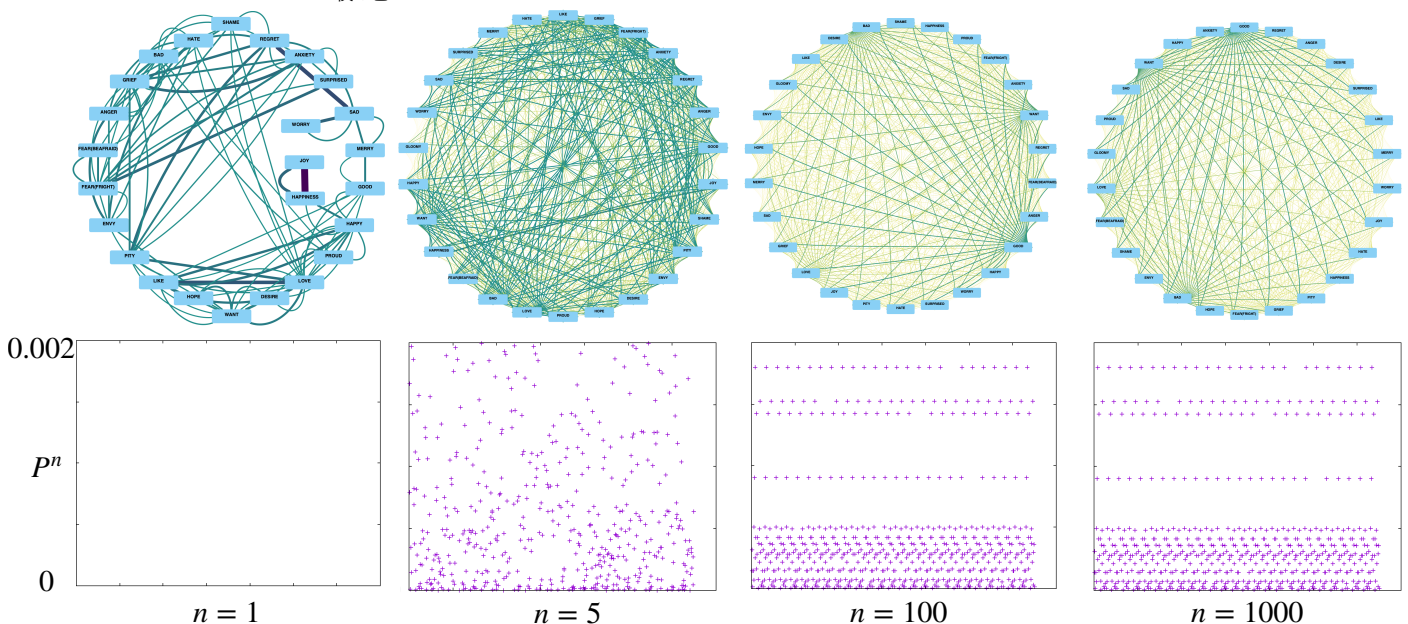
言語全体における感情のつながりを見る

4. 実験結果

枝の重み
枝の色



上段: ネットワーク 下段: 枝の重みプロット



頂点の強度

$$\text{In}_i^n = \sum_j P_{ij}^n$$

$$\text{Out}_i^n = \sum_j P_{ji}^n$$

頂点	In		Out	
	n = 5	n = 1000	n = 5	n = 1000
GOOD	1.08×10^{-1}	4.49×10^{-2}	1.34×10^{-2}	8.75×10^{-3}
WANT	1.13×10^{-1}	3.81×10^{-2}	2.65×10^{-2}	9.02×10^{-3}
BAD	1.20×10^{-1}	3.55×10^{-2}	2.33×10^{-2}	9.12×10^{-3}
LOVE	1.10×10^{-1}	2.26×10^{-2}	4.33×10^{-2}	9.65×10^{-3}
ANGER	3.43×10^{-2}	7.92×10^{-3}	3.92×10^{-2}	1.02×10^{-2}

任意の頂点から出発し
ランダムウォークを行った時、
頂点GOOD・WANT・BAD・LOVEの
4つに到達しやすい
言語の観点では
この4つが基本的な感情

5. まとめ・今後の課題

今回

言語全体における
重要な感情を調査

今後

- ・語族毎に違いはあるか？
- ・地域差はあるか？

言語間の違いに着目

参考文献

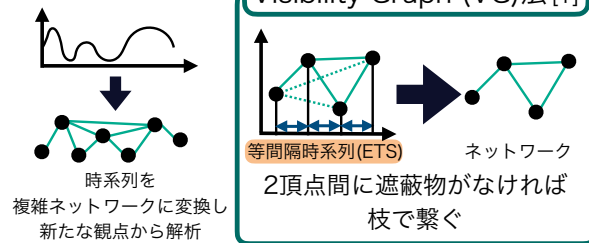
- [1] C. Darwin, *University of Chicago press*, 2015(1872).
- [2] P. Ekman, and D. Lamas, *Macmillan*, 2008.
- [3] J.M. List, C. Rzymiski, T. Tresoldi, S. J. Greenhill, and R. Forkel, <https://clics.cild.org/>, (Last visit Nov. 25th, 2021).
- [4] J. C. Jackson, J. Watts, T. R. Henry, J.M. List, R. Forkel, P. J. Mucha, S. J. Greenhill, R. D. Gray, and K. A. Lindquist, *Science*, Vol. 366, No. 6472, pp. 1517–1522, 2019.

マーク付点過程の時間間隔の差が 重み付きVisibility Graphの構造に与える影響の調査

東京理科大学 池口研究室 B4 森太紀



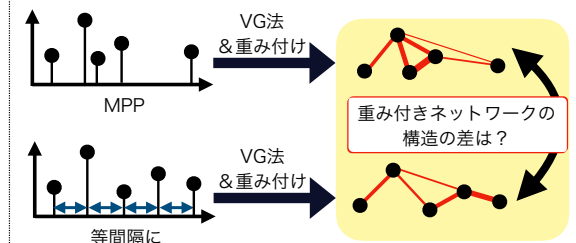
1. 研究背景



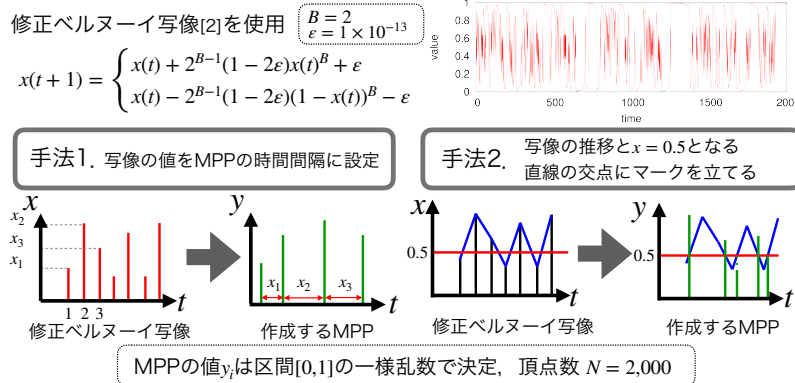
課題

現実世界には…
マーク付点過程(MPP)もある
音楽、生体情報、
地震、経済指標 など
MPPにVG法を
適用して良いのか

2. 目的・実験の流れ



3. MPP作成手法



4. 重み付け

$$\omega_{ij}^{(1)} = \frac{e_{ij}}{e_{\max}}$$

$$\omega_{ij}^{(2)} = \frac{e_{\min}}{e_{ij}}$$

e_{ij} : 頂点 v_i, v_j 間の枝の
ユークリッド距離

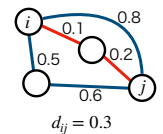
$e_{\max}, e_{\min}$: 枝の距離 e_{ij} の中で
最大, 最小のもの

5. ネットワーク指標

重み付き平均頂点間距離

: 重みを考慮した各頂点間距離の平均

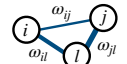
$$L_w = \frac{1}{N^2} \sum_{i,j \in V} d_{ij}, \quad d_{ij} = \min_{\gamma(i,j) \in \Gamma(i,j)} \left\{ \sum_{m,n \in \gamma(i,j)} \omega_{mn} \right\}$$



$\gamma(i,j)$: $\Gamma(i,j)$ に含まれる枝集合, $\Gamma(i,j)$: 頂点 v_i, v_j 間の経路の集合

頂点ごとの重み付きクラスタ係数[3-6]

: 重みを考慮した三角形構造の特徴を表す指標



・Zhang氏の定義[3]

$$C_{w,i}^{(Z)} = \frac{\sum_j \sum_l \omega_{ij} \omega_{jl} \omega_{li}}{(\sum_{j \neq i} \omega_{ij})^2 - \sum_{j \neq i} \omega_{ij}^2}$$

・Lopez-Fernandez氏の定義[4]

$$C_{w,i}^{(L)} = \frac{1}{\sum_{j \in N_G(i)} \omega_{ij} k_j (k_i - 1)}$$

$N_G(i)$: 頂点 v_i を含むサブグラフ
 k_i : 頂点 v_i に接続する枝数

頂点 v_i の対辺の重みを考慮した
三角形構造の割合

・Barrat氏の定義[5]

$$C_{w,i}^{(B)} = \frac{1}{s_i(k_i - 1)} \sum_{j,l} \frac{\omega_{ij} + \omega_{il}}{2} a_{ij} a_{il}$$

$s_i = \sum_j \omega_{ij}$

頂点 v_i に接続する
枝の結合性を考慮

・Onnela氏の定義[6]

$$C_{w,i}^{(O)} = \frac{1}{k_i(k_i - 1)} \sum_{j,l} (\omega_{ij} \omega_{jl} \omega_{li})^{\frac{1}{3}}$$

三角形構造の強度を考慮

6. 実験結果

※平均重み付きクラスタ係数を使用 $C_w = \frac{1}{N} \sum_i C_{w,i}$

※記載している指標は100回分のデータの平均値

(i) 手法1, $\omega^{(1)}$ を使用

	L_w	$C_w^{(Z)}$	$C_w^{(L)}$	$C_w^{(B)}$	$C_w^{(O)}$
MPP	0.7472	0.0065	0.0051	0.7541	0.0041
ETS	0.8128	0.0045	0.0026	0.7659	0.0019

(ii) 手法2, $\omega^{(1)}$ を使用

	L_w	$C_w^{(Z)}$	$C_w^{(L)}$	$C_w^{(B)}$	$C_w^{(O)}$
MPP	0.7649	0.0028	0.0022	0.7607	0.0012
ETS	0.8234	0.0046	0.0026	0.7661	0.0020

距離を使用した重みでは、ネットワーク構造の各指標に差が現れない

(iii) 手法1, $\omega^{(2)}$ を使用

	L_w	$C_w^{(Z)}$	$C_w^{(L)}$	$C_w^{(B)}$	$C_w^{(O)}$
MPP	0.0331	0.0113	0.0099	0.7357	0.0081
ETS	0.9882	0.3730	0.3677	0.7185	0.4271

(iv) 手法2, $\omega^{(2)}$ を使用

	L_w	$C_w^{(Z)}$	$C_w^{(L)}$	$C_w^{(B)}$	$C_w^{(O)}$
MPP	0.2806	0.1517	0.1323	0.7139	0.1398
ETS	0.9876	0.3731	0.3678	0.7188	0.4273

距離の逆数を使用した重みでは、 $C_w^{(B)}$ を除くネットワーク構造の各指標に差が現れた

7. まとめと今後

- 距離の逆数を使用することで、MPPとETSを区別できた。
→非線形力学系から抽出した極大値などでも検証予定。
- 枝の重みの頻度分布がどのようになっているか確認すべき。
→頻度分布によってMPPとETSの変化のしやすさが異なる可能性あり。

参考文献

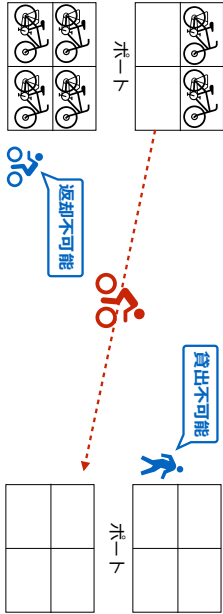
- [1] L. Lacasa, et al., *PNAS*, **105**, 13, 4972–4975, 2008
- [2] Y. Aizawa, et al., *Progress of theoretical physics*, **71**, 4, 847–850, 1984
- [3] B. Zhang, et al., *Statistical applications*, **4**, 1, 2005
- [4] L. Lopez-Fernandez, et al., *MSR*, **2004**, 1, 2004
- [5] A. Barrat, et al., *PNAS*, **101**, 11, 3747–3752, 2004
- [6] J. P. Onnela, et al., *PRE*, **71**, 6, 065103, 2005

バイクシェアリングシステムの利用履歴データ解析

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D2 對馬帆南

非線形・非平衡・非定常系
池口研究室
NONLINEAR DYNAMICAL SYSTEM

1. バイクシェアリングシステム (BSS)



特徴 自由に乗り降り可能、交通渋滞緩和、排気ガス削減

課題 貸出・返却可能なポートが発生

解決策 自転車回収車を用いて再配置作業が必要

2. BSSに関する研究と今回の発表



●: ポート ■: チェスト

ランダムに設置されたオリジナルのベンチマーク問題による提案解法の性能評価

課題 実際の利用履歴情報から得られる情報をベンチマーク問題に組み込む必要がある

著者	H. Tsushima et al. [3,4]	H. Kim et al. [5]
使用したデータ	Boston, Washington D.C., New York, Chicago	Taereungyi
内容	8月のデータを用いて自転車の貸出と返却の発生/パターン解析	季節的な変化とPM1.0/PM2.5がBSSに与える影響
結果	平日と週末、日中と終日の利用/パターンは似ている	PM1.0/PM2.5が高くなると自転車の利用時間は短くなる

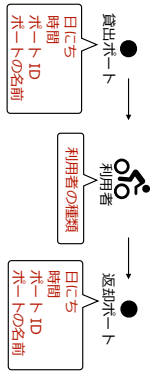
今回の発表

自転車の貸出と返却のタイミングの発生パターンの統計的な特性と属性(会員・非会員)の関係は?

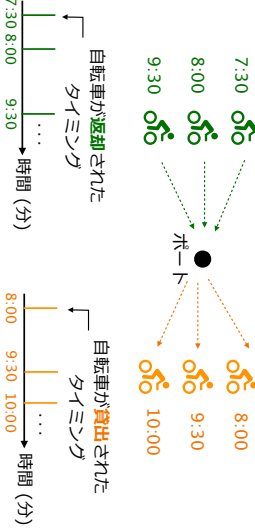
3. BSSの利用履歴に対する統計的な解析

使用するデータと解析方法

都市	ボストン	ワシントン D.C.	シカゴ
名前	Blue Bikes [7]	Capital Bikeshare [8]	Divvy Bikes[6]



自転車が返却、貸出されたタイミングを点過程として扱う



C_Vの結果

(a) ボストン

(b) ワシントン D.C.

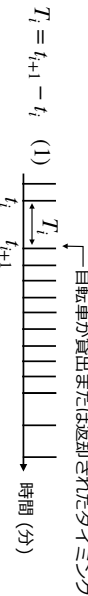
(c) シカゴ

属性考慮なし	平日		週末		平日		週末	
	μ _L	σ _L	μ _L	σ _L	μ _L	σ _L	μ _L	σ _L
会員	1.80 ≤ μ _L ≤ 1.93	1.68 ≤ μ _L ≤ 1.79	1.50 ≤ μ _L ≤ 1.59	1.49 ≤ μ _L ≤ 1.57	1.64 ≤ μ _L ≤ 1.75	1.62 ≤ μ _L ≤ 1.72	1.66 ≤ μ _L ≤ 1.77	1.48 ≤ μ _L ≤ 1.56
非会員	1.71 ≤ μ _L ≤ 1.84	1.46 ≤ μ _L ≤ 1.55	1.55 ≤ μ _L ≤ 1.64	1.46 ≤ μ _L ≤ 1.54	1.36 ≤ μ _L ≤ 1.45	1.59 ≤ μ _L ≤ 1.71	1.38 ≤ μ _L ≤ 1.47	1.55 ≤ μ _L ≤ 1.64

L _V の結果	平日		週末		平日		週末	
	μ _L	σ _L	μ _L	σ _L	μ _L	σ _L	μ _L	σ _L
属性考慮なし	1.12 ≤ μ _L ≤ 1.17	1.25 ≤ μ _L ≤ 1.31	1.16 ≤ μ _L ≤ 1.21	1.31 ≤ μ _L ≤ 1.37	1.11 ≤ μ _L ≤ 1.16	1.23 ≤ μ _L ≤ 1.28	1.08 ≤ μ _L ≤ 1.12	1.15 ≤ μ _L ≤ 1.19
会員	1.09 ≤ μ _L ≤ 1.14	1.14 ≤ μ _L ≤ 1.20	1.14 ≤ μ _L ≤ 1.19	1.25 ≤ μ _L ≤ 1.31	1.08 ≤ μ _L ≤ 1.12	1.15 ≤ μ _L ≤ 1.19	1.03 ≤ μ _L ≤ 1.07	1.13 ≤ μ _L ≤ 1.17
非会員	1.39 ≤ μ _L ≤ 1.44	1.48 ≤ μ _L ≤ 1.54	1.38 ≤ μ _L ≤ 1.47	1.55 ≤ μ _L ≤ 1.64	1.63 ≤ μ _L ≤ 1.71	1.63 ≤ μ _L ≤ 1.71	1.63 ≤ μ _L ≤ 1.71	1.63 ≤ μ _L ≤ 1.71

4. まとめ 局所変動係数の結果から、会員の平日の利用パターンは1に近い値を取る

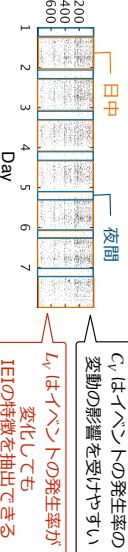
Inter-event-interval (IEI)



変動係数 (C_V): 全てのIEIの変動を測る

$$C_V = \frac{\sqrt{\frac{1}{n-1} \sum_{i=1}^n (T_i - \bar{T})^2}}{\bar{T}}$$

$\bar{T}$: IEIの平均 n : IEIの数



局所変動係数 (L_V): 全てのIEIの局所的な変動を測る [9,10]

$$L_V = \frac{1}{(n-1)} \sum_{i=1}^{n-1} \frac{3(T_i - T_{i+1})^2}{(T_i + T_{i+1})^2}$$

(a) ボストン

(b) ワシントン D.C.

(c) シカゴ

文献 [1] H. Tsushima, et al., "Journal of Signal Processing, 11(4), pp.157-160, 2018. [2] H. Tsushima, et al., "Applied Sciences, 11(16), 7749, 2021. [3] H. Tsushima, et al., "to appear in NOLTA, IECE, E13-542, 2021. [4] H. Tsushima, et al., "to appear in NOLTA, IECE, E13-542, 2021. [5] H. Kim, et al., "Int. J. Environ. Res. Public Health, 17(11), 3999, 2020. [6] Divvy Bikes, https://www.divvybikes.com/system-data. [7] BLUE bikes, https://www.bluebikes.com/system-data. [8] Capital Bikeshare, https://www.capitalbikeshare.com/system-data. [9] S. Shinomoto, et al., "Neural Computation, 15(12), pp. 2823-2842, 2003. [10] S. Shinomoto, et al., "Biometrics, 79(1-2), pp. 67-72, 2005. 本研究は東北大学電気通信研究所における共同プロジェクト研究(P02/A31) による。

P21 言語共起ネットワークのモチーフ解析

東京理科大学 池口研究室

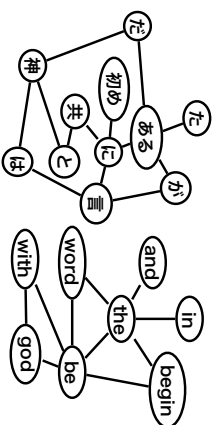
B4 石川竜吉



1. 背景

初めに言があった。
言は神と共にあった。
言は神であった。

In the beginning was the Word,
and the Word was with God,
and the Word was God.

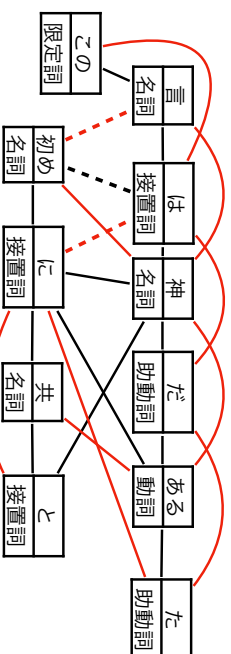


ネットワークを用いて、
言語データを数理的に解析可能

2. 共起ネットワーク

言は神であった。この言は、初めに神と共にあった。

共起数1 —— 共起数2 —— 読点を跨ぐ枝 -----



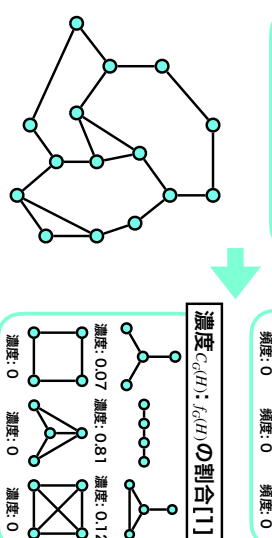
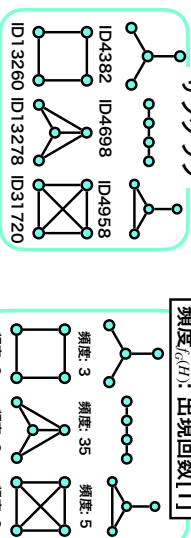
3. 対象データ

福音書 (ヨハネ伝, ムルコ伝, マタイ伝, ルカ伝)

語族	言語	訳/バージョン
シナ・チベット語族	中国語	CSBS
ウラル語族	フィンランド語	UK_1642
		UK_1992
日本語族	日本語	Col
		New
	英語	ESV
		KJV
	フランス語	LSG
		SG21
インド・ヨーロッパ語族	ドイツ語	LB
	ギリシヤ語	NA28
		UBS
	ロシア語	RSV

4. ネットワークモチーフ

サザガラ

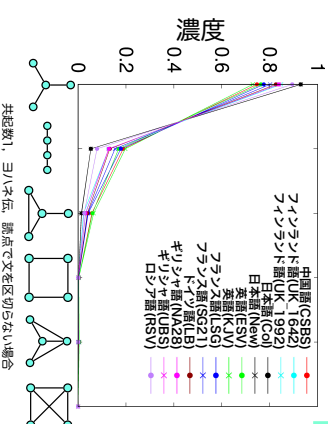


有意性

ランダムサイズ100000回
 $f_b(H) \leq f_a(H)$
100回未満

5. 結果

濃度



有意性

中国語(CSBS)	4382	4698	4958	13260	13278	31710
フィンランド語(UK_1642)	○	×	×	○	×	×
フィンランド語(UK_1992)	○	×	×	○	×	×
日本語(Col)	○	×	×	○	×	×
日本語(New)	○	×	×	○	×	×
英語(ESV)	○	×	×	○	×	×
英語(KJV)	○	×	×	○	×	×
フランス語(LSG)	○	×	×	○	×	×
フランス語(SG21)	○	×	×	○	×	×
ドイツ語(LB)	○	×	×	○	×	×
ギリシヤ語(NA28)	○	×	×	○	×	×
ギリシヤ語(UBS)	○	×	×	○	×	×
ロシア語(RSV)	○	×	×	○	×	×

共起数1, ヨハネ伝, 読点で文を区切らない場合

6. まとめ

ネットワークモチーフ解析によって、
共起ネットワークの構造を調査

それぞれの言語に、
単語同士の接続を媒介する品詞が存在
該当する品詞は、言語によって異なる
読点で文を区切らずに作成すると、
該当する品詞が変化

参考文献

- [1] R. Milo, et al., Science, Vol. 298, No. 5594, pp. 824-827, 2002.
[2] X. Li, et al., PLOS ONE, Vol. 7, No. 12, e50093, 2012.

謝辞

本研究は東北大学電気通信研究所における
共同プロジェクト研究(R02/A31)による。

池口研究室

東京理科大学 池口研究室 B4 福家水月

一、

多義語の曖昧性

① “Душой”: Russian

意味：“BAD”・“UGLY”

類似

②“mauvais”: French

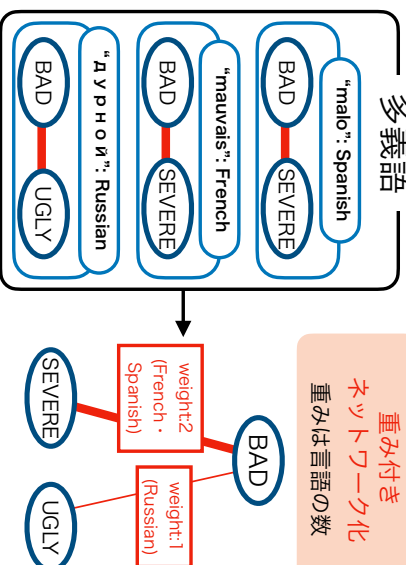
意味: “BAD”・“SEVERE”

類似

多くの多義語に含まれる“BAD”は様々な概念を包含する

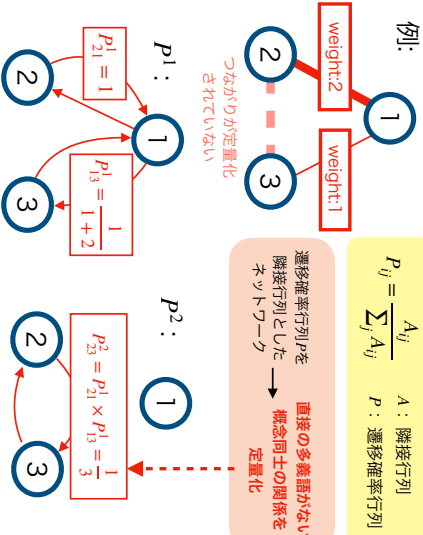
2. ネットワーク作成^[1]

多義語



ランダムウォーク

例:



3. 解析対象

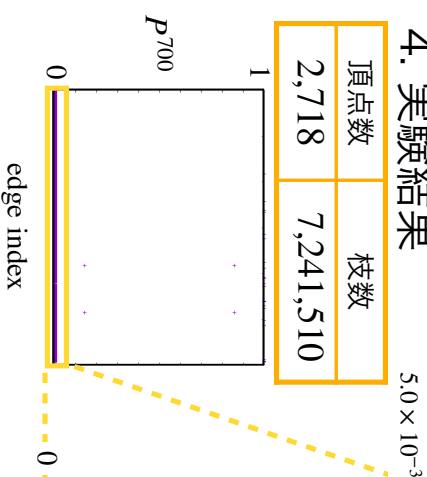
CLICS₃^[2]

- 様々な語族・言語の単語と単語の意味を収録
- 現在使われていない言語も収録
- 同じ語形・意味を多義語と定義

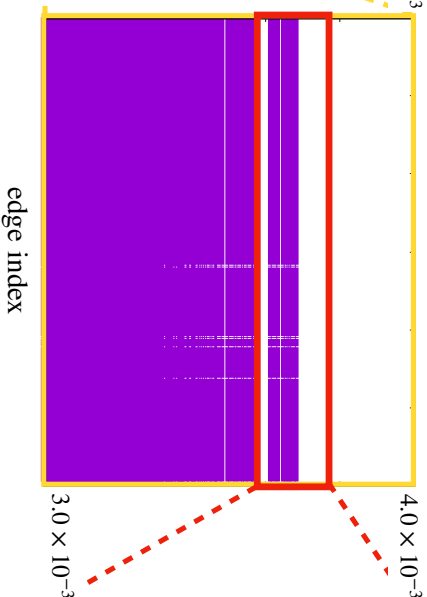
単語数	言語数
1,425,418	3,061

4. 実験結果

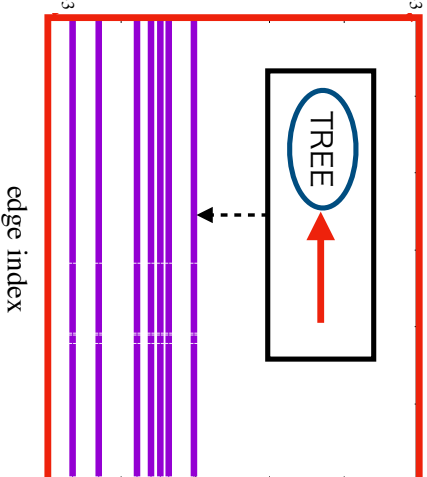
頂点数	枝数
2,718	7,241,510



規模が大きいネットワークの他に
一部の概念で形成される小さいネットワークが
存在する。



枝の重みの範囲が2つに分かれている



最も重みの大い枝に接続している概念は"TREE"

٥٩
٩٥
٧٧
٩٩

多義語ネットワークを用いて中心的概念について調査

中心的概念“TREE”を確認

今後の課題

中心的概念の定義の再確認

別の定義から得られる重要な概念について調査

6. 参考文献

- [1] J. C. Jackson, *et al*, *Science*, **366**, 1517–1522, 2019.
- [2] JM. List, C. Rzymnski, T. Tresoldi, S. J. Greenhill, and R. Forkel, <https://clitics.cild.org/>, (Last visit Nov 25th, 2021).

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受賞, その他



福家水月, 信号処理学会よりNCSP'22
Student Paper Award受賞