Algoritma Pencarian untuk Pemetaan Kecocokan pada Program Pertukaran Ginjal

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Abstrak—Sebelum transplantasi ginjal dilakukan, pendonor dan pasien calon penerima ginjal harus merupakan pasangan yang cocok. Faktanya, tidak jarang ketidakcocokan terjadi di antara pasangan donor-resipien, menimbulkan masalah ketersediaan ginjal. Untuk menyelesaikan masalah ketersediaan ini, Program Pertukaran Ginjal (*Kidney Exchange program*) diciptakan agar pasangan-pasangan ketidakcocokan dapat melakukan pertukaran ginjal dengan pasangan ketidakcocokan lainnya, membuat pendonoran silang. Namun karena sangat banyaknya pasangan ketidakcocokan, mencari pemetaan kecocokan dari sekumpulan pasangan ketidakcocokan bukanlah hal yang mudah. Oleh karena itu, algoritma pencarian pemetaan kecocokan dibuat. Algoritma yang sudah ada, *Edmond's Algorithm*, tidaklah optimal karena sifatnya yang menutup kemungkinan terjadinya pertukaran tiga arah atau lebih. Pada paper ini, dengan memodifikasi algoritma pencarian pemetaan kecocokan dua arah yang sudah ada, diimplementasikan algoritma pencarian pemetaan kecocokan N arah. Berdasarkan hasil pengujian, menggunakan data berisikan 3000 pasangan ketidakcocokan, terbukti bahwa algoritma N arah adalah algoritma yang superior dibandingkan dengan algoritma dua arah apabila diukur menggunakan metrik efisiensi pencocokan (*matching efficiency*). Peningkatan efisiensi pencocokan yang didapatkan secara rata-rata mencapai 7.75% jika dibandingkan dengan efisiensi pencocokan yang didapatkan oleh *Edmond's Algorithm*.

Kata Kunci—transplantasi ginjal, pertukaran ginjal, algoritma pencarian pemetaan kecocokan

I. Pendahuluan

Transplantasi ginjal merupakan metode perawatan yang paling direkomendasikan untuk penyakit-penyakit ginjal yang serius [1]. Setiap tahunnya, di Indonesia sendiri, terdapat lebih dari 100,000 pasien yang memiliki kebutuhan ginjal transplan. Namun hanya sekitar 20% dari pasien-pasien tersebut yang bisa mendapatkan transplantasi [2]. Hal ini terjadi karena adanya masalah finansial, pandangan masyarakat, dan yang paling umum, masalah ketersediaan. Meskipun jumlah pendonor setiap tahunnya semakin meningkat [3], masalah ketersediaan ginjal tetaplah ada dikarenakan oleh banyaknya kriteria medis yang harus dipenuhi oleh pasangan donor-resipien sebelum operasi dapat dilakukan [2]. Pendonor harus memiliki ginjal yang sehat, golongan darah yang cocok dengan resipien, dan tidak memiliki penyakit yang dapat menular melalui darah. Selain itu, sistem imun dari pasien juga harus dapat menerima ginjal pendonor tanpa membunuh ginjal yang bersangkutan.

A. Transplantasi Ginjal

Terdapat beberapa buah pengujian yang harus dilalui sebelum transplantasi ginjal dapat dilakukan [4]. Uji golon-

Tabel I
Kompatibilitas Golongan Darah Penerima dan Pemberi Donor Ginjal [5]

Donor Resipien	O	A	B	AB
O	1	0	0	0
A	1	1	0	0
B	1	0	1	0
AB	1	1	1	1

gan darah dilakukan untuk donor dan juga resipien. Seorang pendonor hanya dapat melakukan pendonoran apabila golongan darah pendonor bersifat cocok dengan golongan darah resipien. Seperti yang dapat dilihat pada Tabel I, angka 1 mengindikasikan kecocokan dan angka 0 mengindikasikan ketidakcocokan. Pendonor dengan golongan darah O merupakan *Universal Donor* karena dapat melakukan donor ke semua golongan darah. Resipien dengan golongan darah AB merupakan *Universal Recipient* karena dapat menerima donor dari semua golongan darah [6]. Uji imunitas dilakukan setelah pasangan donor-resipien melewati uji golongan darah [4]. Terdapat dua jenis pengujian yang dilakukan, yaitu uji silang dan uji *Human Leucocyte Antigen* (HLA). Pada uji silang, darah pendonor dipertemukan dengan darah resipien untuk melihat terjadinya penggumpalan atau tidak. Penggumpalan terjadi apabila sistem imun dari resipien menganggap darah dari pendonor merupakan benda asing yang harus dieksterminasi [7]. Uji HLA juga dilakukan untuk menguji perlawanan dari sistem imun pasien terhadap ginjal pendonor, namun digunakan sel tisu dari pendonor dan resipien melainkan darah [8]. Setelah semua pengujian selesai, uji serologi dilakukan pada pendonor untuk menguji apakah terdapat penyakit yang dapat menular melalui darah pada pendonor [7].

B. Program Pertukaran Ginjal

Karena banyaknya pasangan donor-resipien yang tidak cocok akibat prasyarat-prasyarat transplantasi, program pertukaran ginjal bernama *Kidney Paired Donation* (KPD) diciptakan agar pasangan donor-resipien ketidakcocokan dapat mempertukarkan ginjal dengan pasangan ketidakcocokan lainnya, membuat pendonoran silang menjadi mungkin [5]. Per-
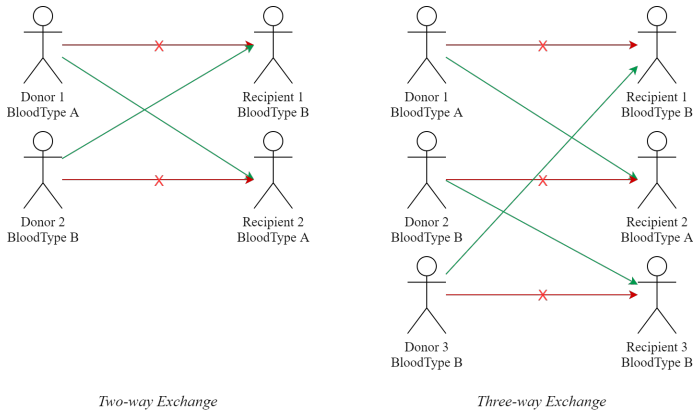
Gambar 1. Pertukaran dua arah(kiri) dan tiga arah(kanan) pada Program Pertukaran Ginjal

tukaran ginjal antar-pasangan dapat dilakukan secara dua arah, tiga arah, dan dapat dilakukan hingga *N* arah.

Karena banyaknya pasangan ketidakcocokan, rumah sakit-rumah sakit tidak dapat secara mudah mendapatkan solusi pencocokan yang optimal untuk sekumpulan pasangan-pasangna ketidakcocokan. Dibutuhkan algoritma untuk mencarikan pemetaan kecocokan. Salah satu algoritma yang diketahui untuk menyelesaikan permasalahan ini adalah *Edmond's Algorithm* [5]. Pada *Edmond's Algorithm*, kumpulan pasangan ketidakcocokan direpresentasikan dengan suatu graf dengan setiap simpul yang adalah pasangan ketidakcocokan dan sisi yang merupakan arah pencocokan antar-pasangan yang mungkin. Algoritma ini berfokus untuk mencarikan kecocokan terlebih dahulu untuk pasangan-pasangan dengan prioritas tinggi sehingga pasien-pasien yang lebih membutuhkan transplantasi dapat mendapatkan pertukaran terlebih dahulu. Algoritma lain pada lingkup kerja ini adalah algoritma *First Accept Heuristic Match* [5] yang menggunakan heuristik dimana pasangan yang registrasi lebih dulu akan mendapatkan kecocokan terlebih dahulu.

Algoritma-algoritma ini dinamakan algoritma pencarian pemetaan kecocokan. Bagus atau tidaknya algoritma-algoritma ini diukur menggunakan metrik performa Efisiensi Pencocokan dan Waktu Eksekusi Algoritma [9]. Efisiensi pencocokan merepresentasikan berapa banyaknya pasangan yang mendapatkan kecocokan dari semua pasangan yang ada, ditulis dalam bentuk persentase. Waktu Eksekusi Algoritma adalah metrik yang mengukur seberapa lama waktu jalannya algoritma dimulai dari *input* masuk hingga *output* keluar, diukur dalam milisekon (ms). Algoritma pencarian pemetaan kecocokan terbaik merupakan algoritma yang mampu menghasilkan efisiensi pencocokan yang tinggi dalam waktu eksekusi yang singkat, yang berarti lebih banyak pasien yang lebih dapat terselamatkan secepat mungkin.

Meskipun *Edmond's Algorithm* dan *First Accept Heuristic Match* sudah ada, algoritma-algoritma tersebut hanya dapat mengembalikan pertukaran dua arah. Hal ini merupakan suatu batasan karena algoritma-algoritma ini menutup kemungkinan dicarikannya solusi dengan pertukaran tiga arah atau lebih.

II. Metodologi

From the existing algorithms problems addressed in the previous section, match map searching algorithms that can find *N*-way exchanges from incompatible pairs pool are needed. By modifying existing algorithms and the used data structure, new algorithms can be created.

A. Compatibility Graph

Before creating new algorithms, incompatibility pairs pool data structure needs to be redefined. Compatibility Graph used in Edmond's Algorithm is an undirected graph [5], meaning that every edge connecting two vertices represent a bidirectional relationship between the aforementioned two vertices, making the returned exchanges to be edges, closing up possibility of three-way exchanges or more. If the algorithm is modified to use cycle detection instead of edge detection, Edmond's Algorithm can already be used to return *N*-way exchanges. As seen in Fig. 2, using cycle detection yields a result with three-way exchange instead of the two-way exchange result returned by edge detection, resulting in a higher matching efficiency using the same compatibility graph.
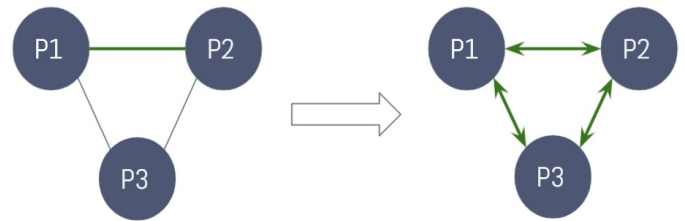
Gambar 2. Edge Detection(left) vs. Cycle Detection(right) in Compatibility Graph

B. Cycle Detection for Directed Graph

As stated in the previous subsection, edge detection used in existing algorithms needs to be converted to cycle detection. However, changing edge detection to cycle detection is not enough. The cycles returned from the graph are all bidirectional cycles. If the compatibility graph is converted into a directed graph instead of undirected, unidirectional cycles can also be returned, further increasing the number of cycles, therefore increasing the matching efficiency. Directed graph is a data structure consisting a set of vertices that are connected via edges, where each edge has a one-way direction that shows the direction of movement from one vertex to another [10]. Cycle detection for directed graph is used to find the existence of a one-way path in a graph that starts and finishes at the same vertex [11].

The cycle detection algorithm being used here is a little bit different from the usual cycle detection algorithm that detects whether a graph has a cycle or not, instead this algorithm collects and returns all possible cycle in a graph in a list. Each cycle in this list is a possible exchange that can be executed. The length of the cycle represents the *N* in *N*-way exchange (e.g., a cycle with the length of 3 represents

a three-way exchange). These modification is performed with the hope that the amount of cycles being detected will increase and therefore increasing matching efficiency and saving more patients.

C. N-way Match Map Searching Algorithms

With directed graph as compatibility graph and using cycle detection algorithm, *N*-way match map searching algorithms can be created. This algorithms receive the list of cycles returned from cycle detection and returned a reduced list of cycles called match mapping. The reduction mentioned is done because each pairs in compatibility graph can exist in more than one cycles in list of cycle, creating a many-to-many relationship among the pairs. This is obviously impossible as every pair can only donate and receive exactly one kidney. The reduction is done to change this many-to-many relationship to be a one-to-one relationship. This reduction usually leaves some pairs to be not matched at all, therefore matching efficiency is used as a performance metric to measure how many pairs can get matched out of the full incompatible pairs pool.

1) First Accept Searching Algorithm: The first *N*-way match map searching algorithm is first accept searching algorithm which is inspired by first accept heuristic match algorithm. The first-accept approach being used in this algorithm is to to use the first cycles in cycles list returned from cycle detection algorithm. This algorithm ensures that no pair gets matched twice or more by deleting cycles that contains pairs that have been matched earlier.

This algorithm uses two parameters. The first parameter is the number of *N*, knowing that this algororithm is an *N*-way algorithm. The second parameter is the method to use *N*. The number of *N* can be used as a maximum or exact way of exchanges. When the maximum method is used, the algorithm will search for cycles that represents two-to-*N*-way exchanges. Meanwhile when exact method is used, the algorithm will search for cycles that have an exact length of *N*.

2) Priority-based Searching Algorithm: The second *N*-way match map searching algorithm is priority-based searching algorithm which is inspired by Edmond's algorithm. This algorithm works similarly with First Accept Searching Algorithm, but each cycle is given a priority value so that exchanges with highest priority can be returned first compared to the others.

This algorothm uses three parameters. The first two are the same parameter used in First Accept Searching Algortihm, number of *N* and the method to use *N*. The third parameter is priority assignment method. There are two methods to measure priority of every cycles. The first assignment method is the greedy method. This method assigns higher priority for longer cycles, indirectly affecting the algorithm to return more of the longer cycles with the hope that it can increase the matching efficiency. The second assignment method is the infrequent method. This method assigns higher priority for cycles with infrequent pairs. In implementation, infrequent pairs are indicated as vertices that are connected with a low

number of edges, meaning that the pairs can only be matched with a low number of other incompatible pairs.

III. EXPERIMENT AND ANALYSIS

Before experiment is performed, Edmond's Algorithm is also implemented as a baseline algorithm so comparisons can be made against an existing algorithm. The data being used in this experiment can be found in this link: https://rdm.inesctec.pt/dataset/ii-2020-001 while the source code of the implementation and the experiment can be found in this link: https://github.com/Mingtaros/Kidney-Exchange-Match-Mapping-System. The purpose of these experiments and evaluations are to find the algorithm and parameter combinations which can produce the best performance results based on pre-defined metrics. In addition, through the experiments, it can be concluded which *N*-way algorithm and parameter combinations are able to outperform the baseline, Edmond's Algorithm. Based on the pre-defined metrics, there will be comparison for Execution Time and Matching Efficiency for each algorithm.

A. Execution Time Comparison

1) Execution Time Comparison for Different Algorithm Combinations: For this experiment, each algorithm is used for 3000 incompatible pairs divided into 30 groups of 100. A group is called a seed. Each algorithm will be fitted with the same dataset group 50 times for every group. As seen in Figure 3, each data point in the boxplot is used to show the average execution time from the 50 executions for every dataset group, in one Y coordinate, there are 30 data points, each one for one data group.
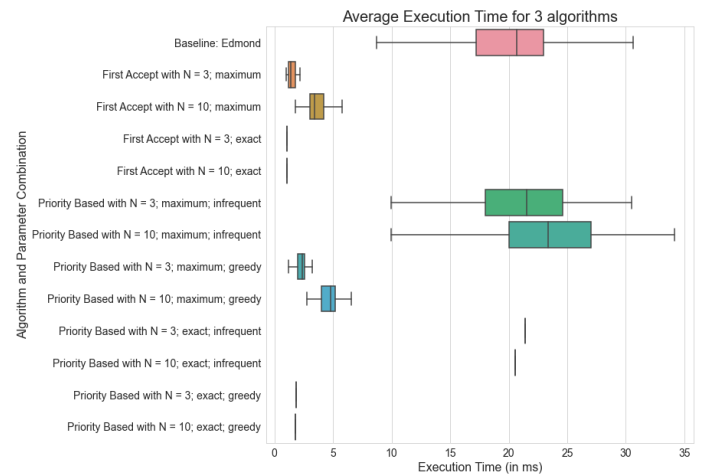

Gambar 3. Average Execution Time for 3 Algorithms

As seen from the boxplot, Edmond's Algorithm and Priority-based with infrequent method of priority assignment are the slowest algorithms. However, given that each and every algorithm does not have a significant difference in execution time, the execution time difference can be ignored.

2) Execution Time Comparison for Different Data Sizes:
This experiment is conducted to show the effect of data size
to execution time of the match map searching algorithms. For
this experiment, the recorded execution time is the average
execution time for each algorithm using data size of 100, 200,
300, 400, 500, 1000, 2000, as well as 3000 incompatible pairs.
Each data point is the average of algorithm execution time that
has been executed 10 times for each algorithm for each data
size.
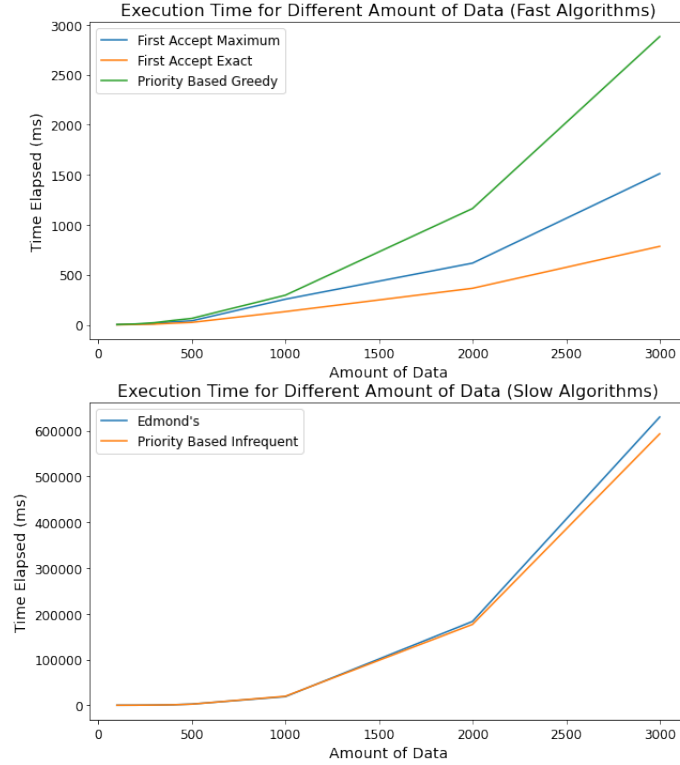
Gambar 4. Execution Time for Different Amount of Data

As seen in Figure 4, there are two plots, each one represent-
ing a group of fast algorithms and a group of slow algorithms.
From the upper figure, even with 3000 incompatible pairs,
the maximum algorithm runtime is around 3000 milliseconds.
Meanwhile, from the lower figure, both of the algorithms
can reach 600000 milliseconds (10 minutes) to process 3000
pairs. From the overall line plot, it can be concluded that the
relation of data size and execution time is a form of polynomial
function, not linear.

B. Overall Matching Efficiency Comparison for Different Algorithms

The final experiment is conducted to show which algorithm-
parameter combination is the best one in producing high
matching efficiency. In this experiment, each combination is
used for every data seed. To ease up the comparison, in Figure
5, ratio of improvement is used in comparison to Edmond's
Algorithm as a baseline shown as a horizontal line in the
figure. Every data point is a matching efficiency multiplier of

the matching efficiency obtained when Edmond's Algorithm
is used.

Gambar 5. Matching Efficiency Ratio of *N*-way Algorithms against Baseline

To simplify the figure, Table II is used to store average
matching efficiency improvement ratio in compared to base-
line. The average used in the table is the average improvement
ratio of an algorithm in comparison to baseline for all data
seeds.

Tabel II
AVERAGE MATCHING EFFICIENCY RATIO OF *N*-WAY ALGORITHMS
COMPARED TO BASELINE

Algorithm	Average Improvement Ratio
Baseline: Edmond's Algorithm	1.0
First Accept(N=3, Method=Max)	1.18
First Accept(N=10, Method=Max)	1.22
First Accept(N=3, Method=Exact)	0.94
First Accept(N=10, Method=Exact)	1.04
Priority Based(N=3, Method=Max, Priority=Greedy)	1.17
Priority Based(N=10, Method=Max, Priority=Greedy)	1.26
Priority Based(N=3, Method=Max, Priority=Infrequent)	1.14
Priority Based(N=10, Method=Max, Priority=Infrequent)	1.16
Priority Based(N=3, Method=Exact, Priority=Greedy)	0.94
Priority Based(N=10, Method=Exact, Priority=Greedy)	1.04
Priority Based(N=3, Method=Exact, Priority=Infrequent)	0.95
Priority Based(N=10, Method=Exact, Priority=Infrequent)	0.91

As can be seen from Table II, most of *N*-way match map
searching algorithm produces higher matching efficiency in
comparison to the baseline, Edmond's Algorithm. However,

some algorithms, using the exact method of using *N* parameter, have worse results compared to baseline. The average matching efficiency of the *N*-way match map searching algorithms is 7.75% higher than the baseline algorithm. The higher matching efficiency improvement is obtained when First Accept Searching algorithm is used when *N* is 10, maximum method of using *N*, with data seed 21, where the improvement against baseline is 47.06%.

While *N*-way match map searching algorithms may produce better results, it is worth noting that with *N*-way exchanges being produced by algorithm may be harder to execute in hospitals since the kidney exchanges have to be operated in the same time. The implication is that exchanges with lower number of ways are easier to conduct as less hospital resources are needed to conduct the operation. Therefore, there needs to be an algorithm comparison regarding the average and the maximum exchanges length of the cycles in the match map. In this experiment, every algorithm and parameter combinations are being tested for 30 data seeds with each containing 100 incompatible pairs.

Gambar 7. Average Match Length for Different Algorithm Combinations
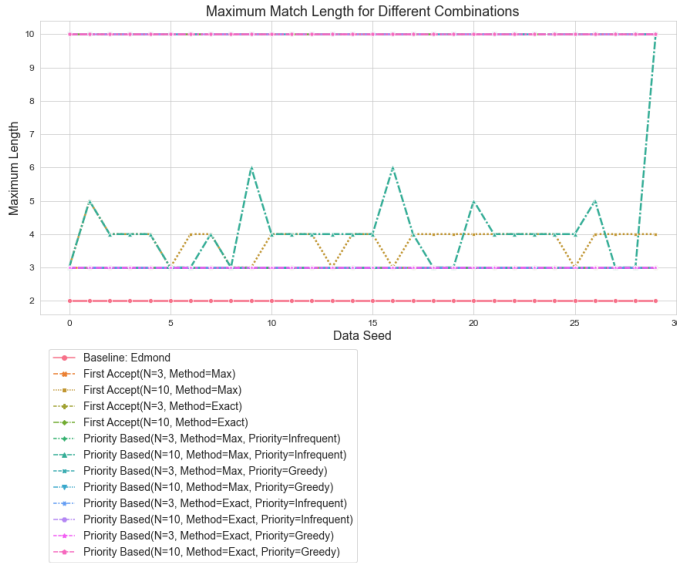
Gambar 6. Maximum Match Length for Different Algorithm Combinations

From what can be seen in Figure 6, Edmond's Algorithm and algorithms with *N* usage method parameter assigned to exact, produced the maximum length of *N* as the cycles in the produced match map is all of the same length that is *N*. The more interesting result is that although the parameter *N* is 10, as can be seen with the green and the yellow line, the maximum length is is not that close to 10.

Similar to what can be seen in Figure 6, in Figure 7, Edmond's Algorithm and algorithms with *N* usage method parameter assigned to exact, produced the average length of *N* as the cycles in the produced match map is all of the same length that is *N*. Generally, almost every algorithm that uses maximum method of *N* usage produces cycles with the average length of around 2 to 3, with Priority-based Searching

algorithm with N=10, Method=Max, and Priority=Greedy, having an averagely high average length of exchanges.

IV. CONCLUSION

This paper shows that it is a viable option to use *N*-way match map searching algorithms instead of the usual two-way algorithms such as Edmond's Algorithm for Kidney Paired Donation, with *N*-way algorithms producing better matching efficiency and competitive execution time in comparison to the baseline, Edmond's Algorithm provided the same dataset. Generally speaking, the usage of *N*-way algorithms increases matching efficiency by 7.75%.

With the provided data, First Accept Searching algorithm have a more consistent performance in general compared to Priority-based Searching algorithm. However, with Priority-based Searching algorithm, the matching efficiency improvement is generally higher with the exception of when exact method to utilize *N* is being used instead of the maximum method. However, it is worth noting that priority-based searching algorithm may produce high matching efficiency with the compromise of high average matching length if greedy priority assignment method is being used. Therefore it can be concluded that First Accept Searching algorithm is the most ideal *N*-way match map searching algorithm to use in Kidney Exchange Program.

V. RELATED WORK

The idea of the solution, the existing algorithms, and the performance metrics being used as a performance measure are all obtained from the main reference paper, Web Based Decision Support System for Kidney Exchange by Samy Raja, Prasanna Devi S., and Suryaprakasa Rao K. in International Journal of Computer Applications [5]. In that paper, two-way match map searching algorithms are being used to tackle the problem of the humanely-impossible task of searching the

most optimal match map out of an incompatible pairs pool, which becomes the baseline and the reference of the newer algorithms being implemented in this paper.

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