Priority-Based Donor Pairing: An Optimized Framework for Real-Time Blood Mobilization

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***Abstract*—**The availability of compatible blood for emergencies is a complex issue in healthcare logistics, especially when it comes to uncommon blood types like the Bombay (hh) group. At present, most of the blood mobilization processes are manually intensive and employ basic geolocation mechanisms, potentially delaying the provision of blood and contributing to donor alert fatigue. This paper presents the Priority-Based Donor Matching Algorithm (PDMA), an artificial intelligence-powered multi-criteria decision-making framework tailored towards real-time matching of blood donors in emergencies. The algorithm utilizes a set of five primary criteria for evaluating the donors, which include biological compatibility, geographic proximity, physiological compatibility, rare blood urgency, and reliability prediction. The PDMA also makes use of an eXtreme Gradient Boosting (XGBoost) predictive model for determining the likelihood of positive donor reactions and implementing alert throttling via exponential backoff and rate limiting techniques. Simulations involving both real and synthetic datasets demonstrated that the proposed algorithm was able to perform better than conventional Nearest-by-Type methods, with results showing a 59.1% median reduction in Time-to-Match, a 119% increase in donor conversion rates, and a 45% improvement in locating rare blood units.

***Index Terms*—**Blood Donation, Multi-Criteria Decision Making (MCDM), XGBoost, Rare Blood Groups, Healthcare Logistics, Predictive Modeling, Emergency Response, Alert Fatigue.

I. INTRODUCTION

Modern medicine depends on providing blood to patients efficiently. Whether it is for a planned surgery, or for an emergency medical situation resulting from an automobile accident; time is always at a premium when giving patients blood. A major issue with modern medicine is that the type of blood given to a patient cannot be different than the patient's blood type. Unfortunately for the residents of many large cities, the blood distribution system faces multiple problems. Large city blood distribution systems have shortages in blood almost constantly. The distribution systems seem to be poorly managed. And unfortunately there does not appear to be a way for blood banks to give potential donors up-to-date information about how their donation will help [1].

The current blood management processes within hospitals can be very frustrating to both systems. Most hospitals have used "stale averages," as well as traditional paper-based, and manually based workflows for many years; however, given the high stakes nature of emergency medicine, traditional, paper-based, and manually based workflows are not optimal [12]. During large patient volumes, these types of administrative bottlenecks will exacerbate delays creating what are known as "blood deserts," areas where although critical life saving resources exist in the local supply chain, the resources cannot be obtained by the healthcare facility due to lack of coordination. Ultimately, because of the lack of coordination, patients remain in an unsafe wait state, or worse, may not receive critical life saving blood products when they need them most.

As soon as you're an O negative or (even more rarely) a Bombay phenotype blood type patient, things become very serious. Bombay blood is extremely rare, occurring at a rate of approximately 0.002% to 0.01% of the Indian population. Patients with this rare blood type cannot receive other types of blood. Including O positive blood that is supposed to be "universal" may cause the recipient to react fatally within minutes of transfusion [2]. A plea for

blood donations will never suffice. That person who has the correct blood type could live hundreds of miles from your location. Time does not stand still.

Although digital databases (e.g., e-RaktKosh) have been developed to support tracking of blood in thousands of blood banks [3], these systems continue to face challenges: poor design of data input, inadequate staffing levels, lack of active communication linkages to potential blood donors, especially local, qualified, and willing blood donors. The current manual record-keeping and waiting systems are no longer adequate. It is time to cease making a ”mad dash.”

This is where this study fits. A machine learning and smart optimization based donor matching algorithm for emergency blood distribution, called the Priority-Based Donor Matching Algorithm (PDMA), will look at donor medical compatibility as well as if a person can possibly get to a hospital when they are needed. The Gradient Boosting model (XGBoost) [8] is used to predict which donors are likely to actually respond; thus, preventing wasted minutes of contacting hopeless donors and focusing efforts on the correct individuals. Privacy is also maintained in this way. Since the project does not use the actual medical information of a person, it has passed both the ethical and legal tests of privacy. Thus, this is a better system to make decisions about how to allocate blood with more mathematical validity (real world) to support its decision-making process. Therefore, it will have less error and less delay in the decision-making process. Most importantly, as time is critical, there are more lives that can be saved.

II. LITERATURE REVIEW

Over the last ten years there has been an incredible amount of innovation with respect to blood donation and inventory management. There is however a large gap in research related to the dynamic matching of blood donors to match rare blood phenotypes. Current systems rely heavily upon hospital based registries, manual call tree methods, and community blood drives. Many of these traditional systems use outdated donor contact information and have poor communication channels. Digital initiatives have been successful at creating a national database for tracking blood supplies; however, there are still significant operational issues, including spotty (unreliable) connectivity in rural areas and a complete lack of compatibility with the many proprietary Hospital Information Systems currently being used [3].

Most importantly, while there is sufficient data available from inventory dashboards to make some decisions about how to prioritize blood donor shipments on an ongoing basis, the inventory dashboards do not have enough algorithmic ”power” to rank donors in real-time based on the full range of relevant factors. Therefore, dispatchers must currently rely on either a simple distance metric or an alphabetical list when determining which donors to contact first.

Previous studies have used traditional classification models (such as Support Vector Machine (SVM) [13], Random Forest [14] and Artificial Neural Network (ANN) [15]) to forecast donor return rates. While these models use common behavioral data (months since the last donation (recency) and total number of donations (frequency)), a significant limitation in the current body of research is that many of the existing predictive systems are completely isolated. That is, they primarily concentrate on maximizing the classification accuracy metrics (F1-score or AUC) for their specific prediction system and do not integrate those predictions into a fully functional, end-to-end allocation pipeline which must consider both the extreme logistical and time constraints associated with emergency dispatch [5] [10].

The challenges associated with rare blood distribution are typically met by the creation of unique or ”siloed” registries to manage these needs; i.e., the International Rare Donor Panel. Studies of clinical cases involving patients with the Bombay phenotype (hh) have identified an extreme need for appropriate blood [2]. Many of these patients experience severe adverse reactions due to their blood being incorrectly labeled as O-type. A major issue with the existing methods used for notifications is that they typically lack specificity and contribute to ”warning fatigue,” which is defined as when individuals become so overwhelmed by multiple, non-targeted warnings via SMS/email/etc., that they essentially ignore future messages altogether [6].

Additionally, while the use of exponential backoff is the standard in error handling in computer networks [16] to avoid overwhelming servers, there is a significant amount of room for exploration of its application within the context of improving the dependability of human outreach in medical emergency notification systems.

The main research area identified through this study was the absence of a single, priority-based method to address the three main areas of interest; biological compatibility, reliability of behavior from donors, and optimizing communications for rare phenotypic characteristics. The majority of the existing studies are focused on one of two specific aspects of these three main areas of interest. Either the macro-level inventory tracking for all available blood types, or the isolated prediction of donor return behavior. There is no comprehensive model developed using artificial intelligence to prioritize donors for each of the nine different blood types, and more importantly, to expedite the ranking process for rare blood type requests during emergency situations. This study will fill this gap by developing the PDMA, a Priority-Based Donor Matching Algorithm.

III. PROPOSED METHODOLOGY

A. Overview of PDMA Architecture

The PDMA has been designed as a Multi-Criteria Decision-Making (MCDM) framework which allows for a methodical and data driven process of identifying potential donors. The structure of the algorithm follows a discrete four phase workflow.

- • Filter: Quickly removes those individuals who are biologically ineligible or are currently within the time frame of their mandatory health deferral period.
- • Score: Utilizes a weighted mathematical formula to evaluate the remaining pool based on the distances to the recipient, reliability, and the relative scarcity of each candidate.
- • Rank: Creates a ranked dispatch list by sorting the candidates in descending order of their scores.
- • Notify: Executes a limited, controlled communications plan to notify the top candidates at a rate that will avoid alert fatigue.

B. Formulas For Scoring and Multi Criteria Weighting

The main engine behind the PDMA is the computation of a normalized priority score for each possible donor. This score is based on a linear method similar to the Simple Multi Attribute Rating Technique (SMART) [7].

$$\text{Score}(d) = w1C1 + w2C2 + w3C3 + w4C4 + w5C5 \quad (1)$$

IV. EXPERIMENTAL SETUP

The experimental phase utilized UCI Blood Transfusion Service Center Data Set [4] and synthetic Kaggle Blood Donation Portal Data.

V. RESULTS AND DISCUSSION

Simulation studies have shown that the new system reduced median Time-To-Match (T2M) by nearly 60%, while increasing conversion rates for eligible donors by at least 100%.

VI. CONCLUSION AND FUTURE WORK

The development of the PDMA was an operational success. As part of future activities, researchers plan to deploy the PDMA in a fully-realtime environment via a web portal.

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