УДК 656.02: 004.051

Zora I.

OPTIMIZATION OF MEMORY USAGE UNDER EXPONENTIAL GROWTH OF A MULTIDIMENSIONAL PASSENGER FLOW MODEL WITH FUZZY PARAMETERS

Vinnytsia National Technical University

Анотація

У роботі досліджено проблему експоненційного зростання обсягу пам'яті при моделюванні пасажиропотоку на міських маршрутах із використанням нечітких множин. Показано, що формування множини станів на кожному кроці розрахунку як декартового добутку призводить до кратного збільшення розмірності моделі та швидкого перевищення допустимого обсягу оперативної пам'яті. Проаналізовано основні підходи до зменшення споживання пам'яті, зокрема агрегацію однакових значень, порогове відсікання малозначущих станів, дискретизацію та квантування, використання розріджених структур даних, редукцію проміжних шарів розрахунку та тензорні декомпозиції. Показано, що застосування зазначених методів дозволяє суттєво зменшити обсяг необхідної пам'яті та забезпечити практичну реалізацію нечіткої моделі пасажиропотоку в умовах обмежених обчислювальних ресурсів.

Ключові слова: нечіткі множини, оптимізація пам'яті, агрегація станів, порогове відсікання, тензорні декомпозиції, транспортні технології.

Abstract

The paper investigates the problem of exponential growth in memory consumption arising in passenger flow modeling on urban routes using fuzzy sets. It is shown that forming the state set at each computation step as a Cartesian product leads to a multiplicative increase in model dimensionality and rapid exceeding of acceptable RAM capacity. The main approaches to reducing memory consumption are analyzed, including aggregation of identical values, threshold pruning of low-significance states, discretization and quantization, the use of sparse data structures, reduction of intermediate computation layers, and tensor decompositions. It is demonstrated that applying these methods significantly reduces the required memory volume and enables practical implementation of fuzzy passenger flow models under limited computational resources.

Keywords: fuzzy sets, memory optimization, state aggregation, pruning, tensor decompositions, transport technologies.

In passenger flow modeling tasks on urban routes using fuzzy sets, the number of possible system states grows exponentially depending on the number of stops and the dimensionality of variable universes. If at each computation step the set of values is formed as a Cartesian product [1]:

$$H_k = \{h_i + p_j - v_l\},$$

where $h_i \in H_{k-1}$, $p_j \in P_k$, $v_l \in V_k$, H_k is the number of passengers after the *k*-th stop, P_k is the number of boarding passengers, V_k is the number of alighting passengers, and each universe contains four values, then the dimensionality of the state set increases by a factor of 16 at each step:

$$|H_k| = 16\,|H_{k-1}|.$$

With an initial size $|H_0| = 4$ after 10 stops:

$$|H_{10}| = 4 \cdot 16^{10} \approx 4{,}4 \times 10^{12}.$$

If each value is stored as a double-precision number (8 bytes), the memory required for the final layer alone reaches:

$$4{,}4 \times 10^{12} \cdot 8 \approx 35\ \text{ТБ}.$$

Even when using 4-byte data types, this exceeds 17 TB of memory. Therefore, the memory issue becomes critical earlier than execution time limitations. The exponential growth of states makes it physically impossible to store the full set of combinations even on modern high-performance systems.

Let's consider possible approaches to reducing memory usage.

Aggregation and elimination of duplicate values - during the formation of the Cartesian product, identical values may arise through different computational paths. Instead of storing all combinations, it is reasonable to retain only unique values with aggregation of their membership degrees. This transforms the complete combinatorial enumeration into a compact set of unique states. In practice, this reduces memory usage from exponential to quasi-linear or polynomial levels [2].

Threshold pruning - in fuzzy models, a significant portion of values has low membership degrees. Introducing a threshold $\mu < \varepsilon$ allows insignificant states to be discarded. This reduces the number of active elements without substantial loss of accuracy [3].

Discretization and quantization - applying a fixed rounding step (quantization) to H_k values leads to merging of close states. This substantially decreases the number of unique states and, consequently, memory usage, although it introduces limited precision loss [4].

Sparse data structures - instead of storing a full dense array, associative containers (hash tables) or sparse representations can be used. In most practical cases, the number of active states is significantly smaller than the theoretical maximum [5].

Recursive reduction without full history storage - rather than storing all intermediate layers, only the current and next layers of computation are maintained. This prevents accumulation of previous states and reduces memory overhead from $O(16^n)$ to $O(16^{n-1})$, although it does not completely eliminate exponential growth, it allows avoiding the accumulation of previous states [6].

Tensor decompositions - representing the multidimensional model using low-rank tensor decompositions (CP, Tucker, Tensor Train) allows memory reduction from exponential to polynomial complexity under low-rank conditions [7].

Modeling results indicate that after applying aggregation and threshold pruning, the number of active states becomes bounded by values determined by the quantization step Δ and the pruning threshold ε. In practical configurations, these parameters limit the number of states to manageable magnitudes 10^4–10^5 at each computation step. Consequently, optimization significantly reduces memory requirements.

Exponential growth of combinations in fuzzy passenger flow modeling leads to critical memory overflow at early computation stages. The core problem lies not only in execution time but also in the physical impossibility of storing the complete state space. The proposed methods such as aggregation, pruning, discretization, sparse structures, and tensor decompositions enable radical memory reduction without substantial loss of accuracy. Their application makes fuzzy transport planning models feasible even on systems with limited computational resources.

REFERENCES

1. Zora, I., & Khoshaba, O. (2025). Use of fuzzy sets in calculating the passenger capacity utilisation rate in conditions where it is impossible to collect objective data. *Information Technologies and Computer Engineering*, 22(1), 115-123. https://doi.org/10.63341/vitce/1.2025.115

2. Pedrycz W., & Chen S. Deep Learning: Algorithms and Applications. *Studies in Computational Intelligence,* SCI, volume 865, Springer, 2020., 360. https://doi.org/10.1007/978-3-030-31760-7

3. Mendel J. Explainable Uncertain Rule-Based Fuzzy Systems (3rd edition). Springer, 2024., 580. https://doi.org/10.1007/978-3-031-35378-9

4. Lang, J., Guo, Z., & Huang, S.. (2024). A Comprehensive Study on Quantization Techniques for Large Language Models. 224-231. DOI:10.1109/ICAIRC64177.2024.10899941.

5. Dongarra, J., et.al. 2011. The International Exascale Software Project roadmap. Int. J. *High Perform. Comput. Appl*. 25, 1 (February 2011), 3–60. https://doi.org/10.1177/1094342010391989

6. Skiena, S., (2020). The Algorithm Design Manual. Springer, 2020., 793. https://doi.org/10.1007/978-3-030-54256-6

7. Cichocki, A., et. al., Tensor Networks for Dimensionality Reduction and Large-Scale Optimizations. Part 2 Applications and Future Perspectives. *Foundations and Trends in Machine Learning*: Vol. 9: No. 6, pp 431-673, 2017. https://doi.org/10.1561/2200000067

Зьора Іван Євгенійович - аспірант кафедри програмного забезпечення, Вінницький національний технічний університет, м. Вінниця, e-mail: ivan.zora@gmail.com.

Науковий керівник: ***Хошаба Олександр Мирославович*** - к.т.н, доцент, доцент кафедри програмного забезпечення, Вінницький національний технічний університет, м. Вінниця.

Ivan Zora - Postgraduate Student of the Department of Software Engineering, Vinnytsia National Technical University, Vinnytsia, e-mail: ivan.zora@gmail.com.

Research supervisor: ***Oleksandr Khoshaba*** - Ph.D., Associate Professor, Associate Professor of the Department of Software Engineering, Vinnytsia National Technical University, Vinnytsia.