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Automated Prediction of Sudoku Puzzle Difficulty Using Convolutional Neural Networks

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Abstract: Predicting the difficulty of mathematical games is a complex task that can be achieved by combining combinatorial analysis with machine learning. In this study, we propose a convolutional neural network-based approach to predict the difficulty level of Sudoku games by considering both the structural attributes of the puzzles and their meta-features. The analysis is conducted over a dataset that consists of about 4 million puzzle grids, each labeled with its solution, number of clues, and difficulty level, which is annotated from 1 (very easy) to 5 (very hard). The puzzle grids are represented as 9x9 numerical arrays, which contain the digits from 0 to 9, where 0s represent the empty positions. On the other hand, the number of clues, which may vary from 17 to 80, is scaled to [0,1] and processed through a small dense branch. In order to make regression-based predictions, we have trained the model with mean absolute error (MAE) as the loss function. The experimental results reached a validation MAE of 0.112, which indicates highly accurate predictions, since the deviation from the true difficulty labels is minimal. This framework that effectively combines the structure of the puzzles and their meta-information for automated difficulty prediction can contribute to game design and game classification in the development of educational tools and adaptive game challenges. Additionally, we have demonstrated that by choosing a regression approach over classification, we have been tracking the closeness of the difficulty levels without ignoring the distance between them.

Keywords: Sudoku difficulty prediction, Convolutional neural networks, Game classification, Recreational mathematics, Machine learning

Introduction

The classification of mathematical games into different difficulty levels is of great importance in game design and adaptive learning platforms. Among such games, Sudoku, as a combinatorial logic puzzle, due to its well-defined rules, great variety of puzzle structures, and measurable difficulty levels, is considered a great test case for automated difficulty prediction. (Kumar, 2021).

Earlier approaches to estimating difficulty typically relied on handcrafted heuristics, such as counting the number of empty cells, the number of attempts to the solution, or identifying other solving techniques. (Cornell University Department of Mathematics, 2009; Higgins et al., 2025). On the other hand, recent advances in machine learning, particularly deep learning, allow models to learn complex patterns directly from raw data. Convolutional Neural Networks (CNNs), known for extracting spatial features from images, can be applied to Sudoku grids to capture these fundamental structural patterns (Gu et al., 2018). Wei (2023) used CNNs combined with difficulty labels, which were derived from depth-first search, and achieved a prediction with an accuracy of 80%. However, their model failed to work on more than 3 difficulty levels. This study proposes a CNN-based framework that combines puzzle grids with the number of given clues, which is considered as meta information of the puzzles, to predict difficulty levels on a continuous scale, providing a fine-grained measure of difficulty. Our aim was also to enlarge the range of the difficulty levels on a scale of 1 to 5.

Method

For this study, we have used a publicly available dataset, which consists of about 4 million Sudoku puzzles (RyanAn, 2022). For each puzzle, we have the puzzle grid, its corresponding solution, the number of clues and the difficulty level. The puzzle grid is represented as a 9x9 numerical array, with digits from 0 to 9, where 0 represents the empty positions. The number of clues has a range from 17 to 80, while the difficulty level is annotated on a scale from 1 (very easy) to 5 (very difficult).

In the preprocessing phase, we have converted the number of clues and scaled them from 0 to 1, and for the difficulty levels, we have used the numerical values for regression analysis. Regarding the splitting of the dataset for training and testing purposes, we have applied a train-test split of 90%-10%. The model that we are proposing for the automated prediction of the difficulty levels uses a dual-branch architecture:

1. Grid branch: A CNN with two convolutional layers (32 and 64 filters) followed by max-pooling, flattening, and dropout for regularization.
2. Clues branch: A single dense layer to process the normalized number of clues.

As it is represented in the following figure, both branches are concatenated and fed into a dense layer with dropout, followed by a final linear output layer to predict the continuous difficulty values.

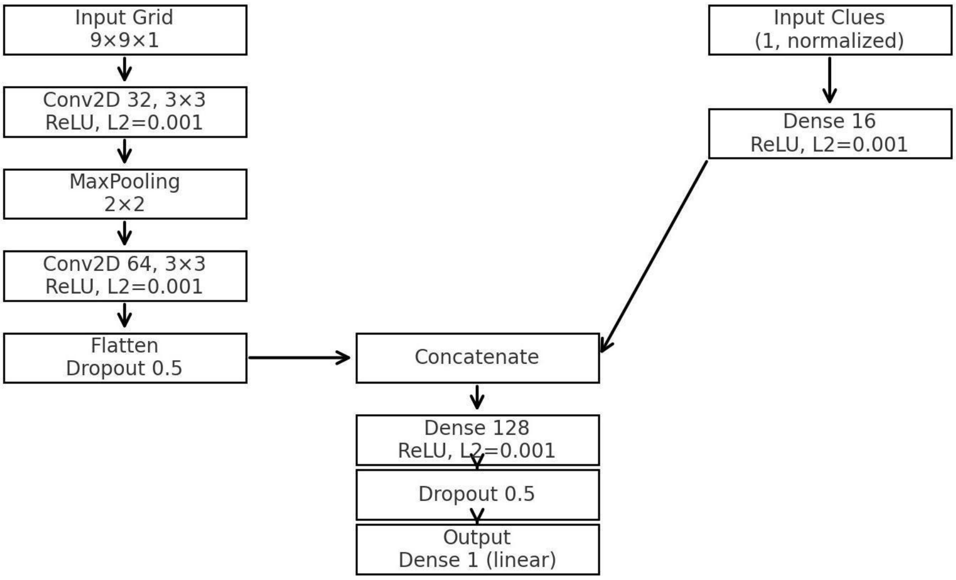

Figure 1. Architecture of the model for Sudoku difficulty prediction

The model was trained using the Adaptive Moment Estimation (Adam) optimizer and Mean Absolute Error (MAE) as the loss function. Adam optimizer is one of the most widely adopted optimization algorithms in deep learning, which combines the advantages of two other extensions of stochastic gradient descent: RMSprop and AdaGrad, making it particularly effective for complex models and large datasets (GeeksforGeeks, 2025).

Results and Discussion

The training of the model was conducted in 20 epochs, with a batch size of 32. The training MAE value stabilized around 0.218, while the validation MAE decreased to 0.114, which indicates a strong generalization. The variations in validation MAE were minor and did not indicate overfitting, meaning that the model effectively learned both grid patterns and meta information (number of clues).

On the testing set, the achieved MAE value of the model was 0.112, which represents a highly accurate prediction. Considering that the difficulty scale is from 1 to 5, this indicates an average deviation of just 0.112 levels from the true values. In the following figure, we may see the values of validation MAE over each epoch, and as it may be noted, the values from the 17^{th} epoch are stabilized.

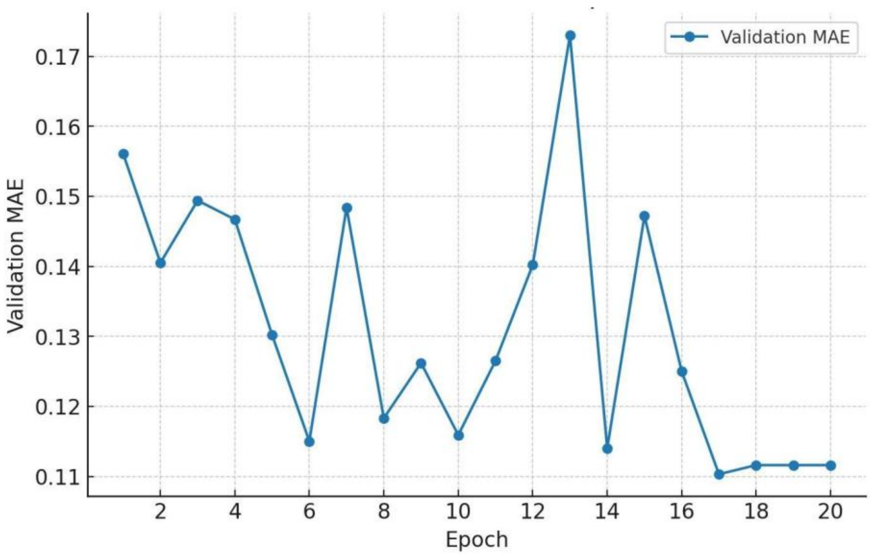

Figure 2. Validation MAE over Epochs

Through the following scatter plot, we have plotted the predicted versus true difficulty levels, and as it may be clearly noticed, the model used assures precise, continuous difficulty predictions. Regarding the distribution across difficulty levels, there is a slightly wider spread around mid-levels; however, this is expected because those levels are harder to distinguish than the extreme ones (very easy or very hard). There can also be seen some outliers where the true difficulty level has been 2, but the predicted level is 3; however, considering the low validating MAE (0.112), those deviations are considered to be small in number.

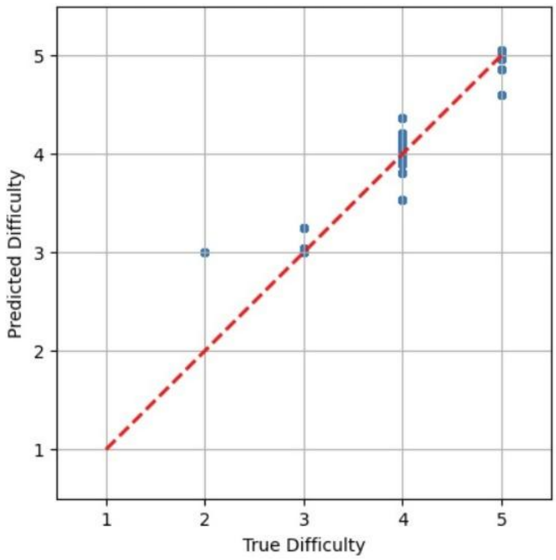

Figure 3. Predicted vs true Sudoku difficulty levels

The scatter plot also demonstrates that using regression maintains the relative closeness between levels, which is important for fine-grained difficulty estimation, where we don't want to ignore those mid-values and treat each level as independent, like the classification approaches do.

Conclusion

This study proposes a Convolutional Neural Network-based regression framework for predicting Sudoku difficulty levels by combining grid structure and meta-information. The model reaches a validation MAE of 0.112, indicating highly accurate predictions. The results demonstrate that the combination of structural features and puzzle-level meta-information can effectively capture puzzle complexity. Regression provides the additional benefit of tracking the relative closeness between difficulty levels, which is essential for applications that require fine-grained difficulty estimation. This framework could be employed to educational platforms for adaptive puzzle generation and classification, and to help in game design by automatically predicting and annotating puzzle difficulty.

Recommendations

For future studies, we recommend including additional meta features of the puzzles, such as symmetry or solving strategies, in order to improve the accuracy of the predictions. This framework can also be applied to other combinatorial or logic-based games to evaluate the generalizability.

Scientific Ethics Declaration

*The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

*The authors declare that they have no conflicts of interest

Acknowledgements or Notes

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