LEARNING CUT SELECTION FOR MIXED-INTEGER LINEAR PROGRAMMING VIA HIERARCHICAL SEQUENCE MODEL

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ABSTRACT

Cutting planes (cuts) are important for solving mixed-integer linear programs (MILPs), which formulate a wide range of important real-world applications. Cut selection—which aims to select a proper subset of the candidate cuts to improve the efficiency of solving MILPs—heavily depends on **(P1)** which cuts should be preferred, and **(P2)** how many cuts should be selected. Although many modern MILP solvers tackle **(P1)-(P2)** by manually designed heuristics, machine learning offers a promising approach to learn more effective heuristics from MILPs collected from specific applications. However, many existing learning-based methods focus on learning which cuts should be preferred, neglecting the importance of learning the number of cuts that should be selected. Moreover, we observe from extensive empirical results that **(P3)** what *order of selected cuts* should be preferred has a significant impact on the efficiency of solving MILPs as well. To address this challenge, we propose a novel **h**ierarchical s**e**quence **m**odel (HEM) to learn cut selection policies via reinforcement learning. Specifically, HEM consists of a two-level model: (1) a higher-level model to learn the number of cuts that should be selected, (2) and a lower-level model—that formulates the cut selection task as a sequence to sequence learning problem—to learn policies selecting an *ordered subset* with the size determined by the higher-level model. To the best of our knowledge, HEM is *the first* method that can tackle **(P1)-(P3)** in cut selection simultaneously from a data-driven perspective. Experiments show that HEM significantly improves the efficiency of solving MILPs compared to human-designed and learning-based baselines on both synthetic and large-scale real-world MILPs, including MIPLIB 2017. Moreover, experiments demonstrate that HEM well generalizes to MILPs that are significantly larger than seen during training.

1 INTRODUCTION

Mixed-integer linear programming (MILP) is a general optimization formulation for a wide range of important real-world applications, such as supply chain management (Paschos, 2014), production planning (Jünger et al., 2009), scheduling (Chen, 2010), facility location (Farahani & Hekmatfar, 2009), bin packing (Nair et al., 2020), etc. A standard MILP takes the form of

$$z^* \triangleq \min_{\mathbf{x}} \{\mathbf{c}^\top \mathbf{x} | \mathbf{A}\mathbf{x} \leq \mathbf{b}, \mathbf{x} \in \mathbb{R}^n, x_j \in \mathbb{Z} \text{ for all } j \in \mathcal{I}\}, \tag{1}$$

where $\mathbf{c} \in \mathbb{R}^n$, $\mathbf{A} \in \mathbb{R}^{m \times n}$, $\mathbf{b} \in \mathbb{R}^m$, x_j denotes the j-th entry of vector $\mathbf{x}$, $\mathcal{I} \subseteq \{1, \ldots, n\}$ denotes the set of indices of integer variables, and z^* denotes the optimal objective value of the problem in 1. However, MILPs can be extremely hard to solve as they are $\mathcal{NP}$-hard problems (Bengio et al., 2021). To solve MILPs, many modern MILP solvers (Gurobi, 2021; Bestuzheva et al., 2021; FICO Xpress, 2020) employ a branch-and-bound tree search algorithm (Land & Doig, 2010), in which a linear programming (LP) relaxation of a MILP (the problem in (1) or its subproblems) is solved at each node. To further enhance the tree search algorithm, cutting planes (cuts) (Gomory, 1960) are introduced to tighten the LP relaxations (Achterberg, 2007; Bengio et al., 2021). Existing work on cuts falls into two categories: cut generation and cut selection (Turner et al., 2022). Cut generation aims to generate cuts, i.e., valid linear inequalities that tighten the LP relaxations (Achterberg, 2007). However, adding all the generated cuts to the LP relaxations can pose a computational problem

Wesselmann & Stuhl (2012). To further improve the efficiency of solving MILPs, cut selection is proposed to select a proper subset of the generated cuts (Wesselmann & Stuhl, 2012). In this paper, we focus on the cut selection problem, which has a significant impact on the overall solver performance (Achterberg, 2007; Tang et al., 2020; Paulus et al., 2022).

Cut selection heavily depends on **(P1)** which cuts should be preferred, and **(P2)** how many cuts should be selected (Achterberg, 2007; Dey & Molinaro, 2018b). Many modern MILP solvers (Gurobi, 2021; Bestuzheva et al., 2021; FICO Xpress, 2020) tackle **(P1)-(P2)** by hard-coded heuristics designed by experts. However, hard-coded heuristics do not take into account underlying patterns among MILPs collected from certain types of real-world applications, e.g., day-to-day production planning, bin packing, and vehicle routing problems (Pochet & Wolsey, 2006; Laporte, 2009; Nair et al., 2020). To further improve the efficiency of MILP solvers, recent methods (Tang et al., 2020; Paulus et al., 2022; Huang et al., 2022) propose to learn cut selection policies via machine learning, which offers promising approaches to learn more effective heuristics by capturing underlying patterns among MILPs from specific applications (Lodi & Zarpellon, 2017; Nair et al., 2020). However, many existing learning-based methods (Tang et al., 2020; Paulus et al., 2022; Huang et al., 2022)—which learn a scoring function to measure cut quality and select a fixed ratio/number of cuts with high scores—suffer from two weaknesses. First, they learn which cuts should be preferred by learning a scoring function, neglecting the importance of learning the number of cuts that should be selected (Dey & Molinaro, 2018b). Moreover, we observe from extensive empirical results that **(P3)** what *order of selected cuts* should be preferred significantly impact the efficiency of solving MILPs as well (see Section 3). Second, they do not take into account the interaction among cuts when learning which cuts should be preferred, as they score each cut *independently*. As a result, they struggle to select cuts that complement each other nicely, which could severely hinder the quality of selected cuts (Dey & Molinaro, 2018b). Indeed, we empirically show that they tend to select many similar cuts with high scores (see Section 5).

To address the aforementioned challenges, we propose a novel **h**ierarchical s**e**quence **m**odel (HEM) to learn cut selection policies via reinforcement learning. To tackle **(P1)-(P3)** in cut selection simultaneously, HEM leverages a two-level model: (1) a higher-level model to learn the number of cuts that should be selected, (2) and a lower-level model to learn policies selecting an *ordered subset* with the size determined by the higher-level model. Specifically, the lower-level model formulates the cut selection task as a sequence to sequence learning problem, which has two main advantages. First, the sequence model naturally captures the order of selected cuts, as it selects cuts sequentially. Second, the sequence model captures the interaction among cuts, as it models the *joint* conditional probability of the selected cuts given an input sequence of the candidate cuts. Experiments show that HEM significantly outperforms human-designed and learning-based baselines in terms of the solving efficiency on three classical synthetic MILP problems and seven challenging MILP problems, including some benchmarks from MIPLIB 2017 (Gleixner et al., 2021) and real-world production planning problems. Our results highlight the ability to enhance modern MILP solvers with our proposed HEM in real-world applications. Moreover, experiments demonstrate that HEM can well generalize to MILPs that are significantly larger than seen during training.

We summarize our major contributions as follows. (1) We observe from extensive empirical results that the *order of selected cuts* has a significant impact on the efficiency of solving MILPs (see Section 3). (2) To the best of our knowledge, our proposed HEM is *the first* method that is able to tackle **(P1)-(P3)** in cut selection simultaneously from a data-driven perspective. (3) We propose to formulate the cut selection task as a sequence to sequence learning problem, which not only captures the order of selected cuts, but also can well capture the interaction among cuts to select cuts that complement each other nicely. (4) Experiments demonstrate that HEM achieves significant improvements over competitive baselines on challenging MILP problems, including some benchmarks from MIPLIB 2017 and real-world production planning problems.

2 BACKGROUND

Cutting planes. Given the MILP problem in (1), we drop all its integer constraints to obtain its *linear programming (LP) relaxation*, which takes the form of

$$z^*_{\text{LP}} = \min_{\mathbf{x}} \{\mathbf{c}^\top \mathbf{x} | \mathbf{A}\mathbf{x} \leq \mathbf{b}, \mathbf{x} \in \mathbb{R}^n\}. \tag{2}$$

Since the problem in (2) expands the feasible set of the problem in (1), we have $z^*_{\text{LP}} \leq z^*$. We denote any lower bound found via a LP relaxation by a *dual bound*. Given the LP relaxation in (2),

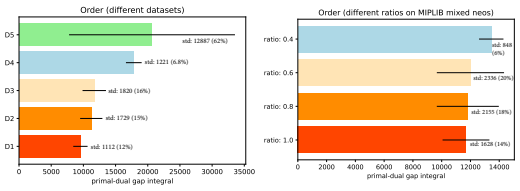
cutting planes (cuts) are linear inequalities that are added to the original problem in (1) in the attempt to tighten the LP relaxation without removing any integer feasible solutions of the problem in (1). Cuts generated by MILP solvers are added in successive rounds. Specifically, each round k involves (i) solving the current LP relaxation, (ii) generating a pool of candidate cuts $\mathcal{C}^k$, (iii) selecting a subset $\mathcal{S}^k \subseteq \mathcal{C}^k$, (iv) adding $\mathcal{S}^k$ to the current LP relaxation to obtain the next LP relaxation , (v) and proceeding to the next LP relaxation. Although adding all the generated cuts to the formulation would maximally strengthen the LP relaxation and improve the lower bound at each round, adding too many cuts could lead to large models, which can increase the computational burden and present numerical instabilities (Wesselmann & Stuhl, 2012; Paulus et al., 2022). Therefore, selecting a proper subset of the candidate cuts, namely cut selection, is significant for improving the efficiency of solving MILPs (Dey & Molinaro, 2018b; Tang et al., 2020).

Branch-and-cut. In modern MILP solvers, cutting planes are often combined with the branch-and-bound algorithm (Land & Doig, 2010), which is known as the branch-and-cut algorithm (Bengio et al., 2021). Branch-and-bound techniques perform implicit enumeration by building a search tree, in which every node represents a subproblem of the original problem in (1). The solving process begins by selecting a leaf node of the tree and solving its LP relaxation. Let $\mathbf{x}^*$ be the optimal solution of the LP relaxation. If $\mathbf{x}^*$ violates the original integrality constraints, two subproblems (child nodes) of the leaf node are created by *branching*. Specifically, the leaf node is added with constraints $x_i \leq \lfloor x_i^* \rfloor$ and $x_i \geq \lceil x_i^* \rceil$, respectively, where x_i denotes the i-th variable, x_i^* denotes the i-th entry of vector $\mathbf{x}^*$, and $\lfloor\rfloor$ and $\lceil\rceil$ denote the floor and ceil functions. In contrast, if $\mathbf{x}^*$ is a (mixed-)integer solution of (1), then we obtain an upper bound on the optimal value of (1), which we denote by *primal bound*. In modern MILP solvers, the addition of cutting planes is alternated with the *branching* phase. That is, cuts are added at nodes of the search tree before branching to tighten their LP relaxations. Since strengthening the relaxation before starting to branch is decisive to ensure an efficient tree search (Wesselmann & Stuhl, 2012; Bengio et al., 2021), we focus on only adding cuts at the root node, which follows (Huang et al., 2022; Paulus et al., 2022).

Primal-dual gap integral. We keep track of two important bounds when running branch-and-cut, including the global primal and dual bound, which are the best upper bound and lower bound on the optimal value of (1), respectively. We define the *primal-dual gap integral* (PD integral) by the area between the curve of the solver's global primal bound and the curve of the solver's global dual bound. In the NeurIPS 2021 ML4CO competition (Bowly et al., 2021), the primal-dual gal integral is set as a primary evaluation metric. We provide additional details in Appendix C.1.

3 MOTIVATING RESULTS

We first empirically show that the *order of selected cuts*, i.e., the selected cuts are added to the problem in (1) in this order, significantly impact the efficiency of solving MILPs. We then empirically show that the *ratio of selected cuts* matters significantly when solving MILPs as well. Due to limited space, we present the latter results in Appendix F.1. Please refer to Appendix D.2 for details of the datasets used in this section.



(a) Evaluate RandomAll on five different datasets. (b) Evaluate RandomNv on MIPLIB mixed neos.

Figure 1: We design two cut selection heuristics, namely RandomAll and RandomNV (see Section 3 for details), which always select the same subset of cuts for a given MILP and then vary the order of the selected cuts. The results in (a) and (b) show that adding cuts with different order leads to variable overall solver performance.

Order matters. Previous work (Bixby, 1992; Maros, 2002; Li et al., 2022) has shown that the order of constraints for a given linear program (LP) greatly impact its constructed initial basis, which is significant for the efficiency of solving LPs. Due to the fact that a cut is a linear constraint, adding cuts to the LP relaxation is equivalent to adding constraints to the LP relaxation. Therefore, we hypothesize that the order of added cuts should have a large impact on solving the LP relaxation, thereby being significant for solving MILPs. (1) To evaluate whether the order of selected cuts affects the efficiency of solving MILPs, we first design a RandomAll cut selection rule, which randomly permutes all the candidate cuts and adds all the cuts to the formulation. RandomAll always selects all the cuts, but the order of selected cuts is very variable. We evaluate RandomAll on five challenging datasets that are inspired by real-world applications. We measure the solver performance with the average PD integral within a time limit

of 300 seconds, and use SCIP 8.0.0 (Bestuzheva et al., 2021) as the backend solver. As shown in Figure 1a, the performance of the solver with RandomAll on each dataset varies with the order of selected cuts. (2) To further evaluate the impact of the order of selected cuts with different given ratios, we then design a RandomNV cut selection rule, which selects a given ratio of cuts based on the Normalized Violation (NV) method (Huang et al., 2022) and randomly permutes the selected cuts. The NV method scores each cut via the extent to which it is violated by the optimal solution of the LP relaxation and selects a given ratio of cuts with high scores. RandomNV with a given ratio always selects the same subset, but the order of selected cuts is variable. The results in Figure 1b show that RandomNV with a given ratio achieves variable solver performance on the same dataset.

4 LEARNING CUT SELECTION VIA HIERARCHICAL SEQUENCE MODEL

Although the optimal labels in the cut selection task are inaccessible, one can assess the quality of selected subsets using a solver and provide some reward feedbacks. Therefore, we leverage reinforcement learning (RL) to learn cut selection policies as Tang et al. (2020). In this section, we provide a detailed description of our proposed RL framework for learning cut selection. First, we present our formulation of the cut selection as a Markov decision process (MDP) (Sutton & Barto, 2018). Then, we present a detailed description of our proposed **h**ierarchical s**e**quence **m**odel (HEM). Finally, we derive a hierarchical policy gradient for training HEM efficiently.

Reinforcement Learning Formulation

As shown in Figure 2, we regard a MILP solver as an environment and our proposed hierarchical sequence model as an agent. Specifically, we specify the state space $\mathcal{S}$, the action space $\mathcal{A}$, the reward function $r : \mathcal{S} \times \mathcal{A} \to \mathbb{R}$, the transition function f, and the terminal state in the following. **(1) The state space $\mathcal{S}$.** Since the current LP relaxation and the generated cuts contain the core information for cut selection, we define a state s by $(M_{\text{LP}}, \mathcal{C}, \mathbf{x}^*_{\text{LP}})$, where M_{LP} denotes the mathematical model of the current LP relaxation, $\mathcal{C}$ denotes the set of the candidate cuts, and $\mathbf{x}^*_{\text{LP}}$ denotes the optimal solution of the LP relaxation. To encode the state information, we follow (Achterberg, 2007; Huang et al., 2022) to design thirteen features for each candidate cut based on the information of $(M_{\text{LP}}, \mathcal{C}, \mathbf{x}^*_{\text{LP}})$. That is, we represent a state s by a sequence of thirteen-dimensional feature vectors. We present details of the designed features in Appendix E.1. **(2) The action space $\mathcal{A}$.** Previous work (Achterberg, 2007; Turner et al., 2022) defines the action space as all the subsets of the candidate cuts $\mathcal{C}$, which does not take into account the order of selected cuts. However, we empirically show that the order of selected cuts matters significantly when solving MILPs in Section 3. To capture the effect of the order, we define the action space by all the *ordered* subsets of the candidate cuts $\mathcal{C}$. It can be challenging to explore the action space efficiently, as the cardinality of the action space can be extremely large due to its combinatorial structure. **(3) The reward function r.** To evaluate the effect of the added cuts on solving MILPs, we design the reward function by (i) measures collected at the end of solving LP relaxations such as the dual bound improvement, (ii) and end-of-run statistics, such as the solving time and the primal-dual gap integral. For the first, the reward $r(s, a)$ can be defined as the dual bound improvement at each step. For the second, the reward $r(s, a)$ can be defined as zero except the last (s_T, a_T) in a trajectory, i.e., we define $r(s_T, a_T)$ by the solving time or the primal-dual gap integral. **(4) The transition function f.** The transition function maps the current state s and the action a to the next state s', where s' represents the next LP relaxation generated by adding the selected cuts at the current LP relaxation. **(5) The terminal state.** There is no standard and unified criterion to terminate the cut separation, i.e., how many times the separation procedure should be repeated (Paulus et al., 2022). In this paper, we set the cut separation rounds T as one following (Huang et al., 2022). Nevertheless, we emphasize that our proposed RL framework can be easily applied to the multiple rounds setting, i.e., $T > 1$. If $T = 1$, then the decision problem is a one-step decision problem. More precisely, it is a contextual bandit (Sutton & Barto, 2018).

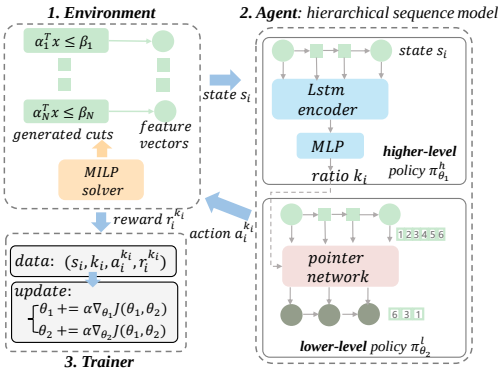


Figure 2: Illustration of our proposed RL framework for learning cut selection policies. We regard a MILP solver as the environment and the HEM as the agent. Moreover, we train HEM via a hierarchical policy gradient algorithm.

Hierarchical Sequence Model

Motivation. Based on the aforementioned formulation, we define the cut selection policy by $\pi : \mathcal{S} \to \mathcal{P}(\mathcal{A})$, where $\mathcal{P}(\mathcal{A})$ denotes the probability distribution over the action space and $\pi(\cdot|s)$ denotes the probability distribution over the action space given the state s. We emphasize that learning such policies can tackle **(P1)-(P3)** in cut selection simultaneously. However, directly learning such policies can be challenging for the following reasons. First, it is difficult to explore the action space efficiently, as the cardinality of the action space can be extremely large due to its combinatorial structure. Second, the length and max length of actions (i.e., ordered subsets) are variable across different MILPs. However, traditional reinforcement learning usually deal with problems whose actions have a fixed length. Instead of directly learning the aforementioned policy, many existing learning-based methods (Tang et al., 2020; Huang et al., 2022; Paulus et al., 2022) learn a scoring function to measure cut quality and select a fixed ratio/number of cuts with high scores. However, they have two main drawbacks as mentioned in Section 1.

Policy network architecture. To tackle the problems, we propose a novel hierarchical sequence model (HEM) to learn cut selection policies. To promote efficient exploration, HEM leverages the hierarchical structure of the cut selection task to decompose the policy into two sub-policies, i.e., a higher-level policy π^h and a lower-level policy π^l (see Figure 2). **First**, the higher-level policy learns the number of cuts that should be selected by predicting a proper ratio. Suppose the length of the state is N and the predicted ratio is k, then the predicted number of cuts that should be selected is $\lfloor N * k \rfloor$, where $\lfloor \cdot \rfloor$ denotes the floor function. We define the higher-level policy by $\pi^h : \mathcal{S} \to \mathcal{P}([0, 1])$, where $\pi^h(\cdot|s)$ denotes the probability distribution over $[0, 1]$ given the state s. **Second**, the lower-level policy learns to select an ordered subset with the size determined by the higher-level policy. We define the lower-level policy by $\pi^l : \mathcal{S} \times [0, 1] \to \mathcal{P}(\mathcal{A})$, where $\pi^l(\cdot|s, k)$ denotes the probability distribution over the action space given the state s and the ratio k. To capture the interaction among cuts and the order of selected cuts, we formulate the lower-level policy as a sequence model. **Finally**, we derive the cut selection policy via the law of total probability, i.e., $\pi(a_k|s) = \mathbb{E}_{k \sim \pi^h(\cdot|s)}[\pi^l(a_k|s, k)]$, where k denotes the given ratio and a_k denotes the action. The policy is computed by an expectation, as a_k cannot determine the ratio k. For example, suppose that $N = 100$ and the length of a_k is 10, then the ratio k can be any number in the interval $[0.1, 0.11)$.

For the higher-level policy, we first model the higher-level policy as a tanh-Gaussian, i.e., a Gaussian distribution with an invertible squashing function ($\tanh$), which is commonly seen in deep reinforcement learning (Schulman et al., 2017; Haarnoja et al., 2018). The mean and covariance of the Gaussian are given by neural networks. The support of the tanh-Gaussian is $[-1, 1]$, but a valid ratio of selected cuts should belong to $[0, 1]$. Thus, we further perform a linear transformation on the tanh-Gaussian. Specifically, we define the parameterized higher-level policy by $\pi^h_{\theta_1}(\cdot|s) = 0.5 * \tanh(K) + 0.5$, where $K \sim \mathcal{N}(\mu_{\theta_1}(s), \sigma_{\theta_1}(s))$. Since a state is a sequence of feature vectors whose length is variable across different instances, we use a long-short term memory (LSTM) (Hochreiter & Schmidhuber, 1997) network to embed the sequence of candidate cuts. We then use a multi-layer perceptron (MLP) (Goodfellow et al., 2016) to predict the mean and covariance from the last hidden state of the LSTM encoder.

For the lower-level policy, we formulate it as a sequence model. That is, its input is a sequence of candidate cuts, and its output can be any ordered subset of candidate cuts with the size determined by the higher-level policy. Specifically, given a state action pair (s, k, a_k), the sequence model computes the conditional probability $\pi^l_{\theta_2}(a_k|s, k)$ using a parametric model to estimate the terms of the probability chain rule, i.e., $\pi^l_{\theta_2}(a_k|s, k) = \prod_{i=1}^{m} p_{\theta_2}(a_k^i|a_k^1, \ldots, a_k^{i-1}, s, k)$. Here $s = \{s^1, \ldots, s^N\}$ is a sequence of N cut feature vectors, $m = \lfloor N * k \rfloor$ is the length of the output sequence, and $a_k = \{a_k^1, \ldots, a_k^m\}$ is a sequence of m indices, each corresponding a position in the input sequence s. Such policy can be parametrized by vanilla sequence model commonly used in machine translation (Sutskever et al., 2014; Vaswani et al., 2017). However, the number of candidate cuts varies on different instances, even if the instances are from the same class of problems. Thus, the vanilla sequence model can only be applied to learning on a single instance. To generalize across different instances, we use a pointer network (Vinyals et al., 2015; Bello* et al., 2017)—which uses attention as a pointer to select a member of the input sequence as the output at each decoder step—to parametrize $\pi^l_{\theta_2}$ (see Appendix E.4 for details). To the best of our knowledge, we are the first to formulate the cut selection task as a sequence to sequence learning problem and apply the pointer network to cut selection, which has two main advantages as mentioned in Section 1.

Training: hierarchical policy gradient

For the cut selection task, we aim to find θ that maximizes the expected reward over all trajectories

$$J(\theta) = \mathbb{E}_{s\sim\mu, a_k\sim\pi_\theta(\cdot|s)}[r(s, a_k)], \tag{3}$$

where $\theta = [\theta_1, \theta_2]$ with $[\theta_1, \theta_2]$ denoting the concatenation of the two vectors, $\pi_\theta(a_k|s) = \mathbb{E}_{k\sim\pi^h_{\theta_1}(\cdot|s)}[\pi^l_{\theta_2}(a_k|s, k)]$, and μ denotes the initial state distribution.

To train the policy with a hierarchical structure, we derive a hierarchical policy gradient following the well-known policy gradient theorem (Sutton et al., 1999a; Sutton & Barto, 2018).

Proposition 1. *Given the cut selection policy $\pi_\theta(a_k|s) = \mathbb{E}_{k\sim\pi^h_{\theta_1}(\cdot|s)}[\pi^l_{\theta_2}(a_k|s, k)]$ and the training objective (3), the hierarchical policy gradient takes the form of*

$$\nabla_{\theta_1} J([\theta_1, \theta_2]) = \mathbb{E}_{s\sim\mu, k\sim\pi^h_{\theta_1}(\cdot|s)}[\nabla_{\theta_1} \log(\pi^h_{\theta_1}(k|s))\mathbb{E}_{a_k\sim\pi^l_{\theta 2}(\cdot|s,k)}[r(s, a_k)]],$$
$$\nabla_{\theta_2} J([\theta_1, \theta_2]) = \mathbb{E}_{s\sim\mu, k\sim\pi^h_{\theta_1}(\cdot|s), a_k\sim\pi^l_{\theta_2}(\cdot|s,k)}[\nabla_{\theta_2} \log \pi^l_{\theta_2}(a_k|s, k) r(s, a_k)].$$

We provide detailed proof in Appendix A. We use the derived hierarchical policy gradient to update the parameters of the higher-level and lower-level policies. We implement the training algorithm in a parallel manner that is closely related to the asynchronous advantage actor-critic (A3C) (Mnih et al., 2016). Due to limited space, we summarize the procedure of the training algorithm in Appendix E.6. Moreover, we discuss some additional advantages of HEM (see Appendix E.7 for details). (1) HEM leverages the hierarchical structure of the cut selection task, which is important for efficient exploration in complex decision-making tasks (Sutton et al., 1999b). (2) HEM can be trained via gradient-based algorithms, which is sample efficient (Sutton & Barto, 2018).

5 EXPERIMENTS

Our experiments have five main parts: **#Experiment 1.** Evaluate our approach on three classical synthetic MILP problems and six challenging MILP problem benchmarks from diverse application areas. **#Experiment 2.** Perform carefully designed ablation studies of our approach. **#Experiment 3.** Test whether HEM can generalize to instances significantly larger than seen during training. **#Experiment 4.** Visualize the cuts selected by our method compared to the baselines. **#Experiment 5.** Deploy our approach to real-world production planning problems.

Benchmarks. We evaluate our approach on nine $\mathcal{NP}$-hard MILP problem benchmarks, which consist of three classical synthetic MILP problems and six challenging MILP problems from diverse application areas. We divide the nine problem benchmarks into three categories according to the difficulty to solve them using the SCIP 8.0.0 solver (Bestuzheva et al., 2021). We call the three categories easy, medium, and hard datasets, respectively. (1) *Easy datasets* consist of three widely used synthetic MILP problem benchmarks: Set Covering (Balas & Ho, 1980), Maximum Independent Set (Bergman et al., 2016), and Multiple Knapsack (Scavuzzo et al., 2022). We artificially generate instances following (Gasse et al., 2019; Sun et al., 2020). (2) *Medium datasets* consist of MIK (Atamtürk, 2003) and CORLAT (Gomes et al., 2008), which are widely used benchmarks for evaluating MILP solvers (He et al., 2014; Nair et al., 2020). (3) *Hard datasets* include the Load Balancing problem, inspired by real-life applications of large-scale systems, and the Anonymous problem, inspired by a large-scale industrial application (Bowly et al., 2021). Moreover, hard datasets contain benchmarks from MIPLIB 2017 (MIPLIB) (Gleixner et al., 2021). Although Turner et al. (2022) has shown that directly learning over the full MIPLIB can be extremely challenging, we propose to learn over subsets of MIPLIB. We construct two subsets, called MIPLIB mixed neos and MIPLIB mixed supportcase. Due to limited space, please see Appendix D.1 for details of these datasets.

Experimental setup. Throughout all experiments, we use SCIP 8.0.0 (Bestuzheva et al., 2021) as the backend solver, which is the state-of-the-art open source solver and is widely used in research of machine learning for combinatorial optimization (Gasse et al., 2019; Huang et al., 2022; Turner et al., 2022; Nair et al., 2020). Following (Gasse et al., 2019; Huang et al., 2022; Paulus et al., 2022), we only allow cutting plane generation and selection at the root node and set the cut separation rounds as one. All other SCIP parameters are kept to default so as to make comparisons as fair and reproducible as possible. We emphasize that all of the SCIP solver's advanced features, such as presolve and heuristics, are open, which ensures that our setup is consistent with the realistic setting. Throughout all experiments, we set the default time limit as 300 seconds. For completeness,

Table 1: Policy evaluation on easy, medium, and hard datasets. The best performance are marked in bold. In all datasets, m denotes the average number of constraints and n denotes the average number of variables. We report the arithmetic mean (standard deviation) of the Time and PD integral.

	Easy: Set Covering ($n = 1000,\ m = 500$)			Easy: Max Independent Set ($n = 500,\ m = 1953$)			Easy: Multiple Knapsack ($n = 720,\ m = 72$)		
Method	Time(s) ↓	Improvement (time, %) ↑	PD integral ↓	Time(s) ↓	Improvement (time, %) ↑	PD integral ↓	Time(s) ↓	Improvement (time, %) ↑	PD integral ↓
NoCuts	6.31 (4.61)	NA	56.99 (38.89)	8.78 (6.66)	NA	71.31 (51.74)	9.88 (22.24)	NA	16.41 (14.16)
Default	4.41 (5.12)	29.90	55.63 (42.21)	3.88 (5.04)	55.80	29.44 (35.27)	9.90 (22.24)	-0.20	16.46 (14.25)
Random	5.74 (5.19)	8.90	67.08 (46.58)	6.50 (7.09)	26.00	52.46 (53.10)	13.10 (35.51)	-32.60	20.00 (25.14)
NV	9.86 (5.43)	-56.50	99.77 (53.12)	7.84 (5.54)	10.70	61.60 (43.95)	13.04 (36.91)	-32.00	21.75 (24.71)
Eff	9.65 (5.45)	-53.20	95.66 (51.71)	7.80 (5.11)	11.10	61.04 (41.88)	9.99 (19.02)	-1.10	20.49 (22.11)
SBP	1.91 (0.36)	69.60	38.96 (8.66)	2.43 (5.55)	72.30	21.99 (40.86)	7.74 (12.36)	21.60	16.45 (16.62)
HEM (Ours)	**1.85 (0.31)**	**70.60**	**37.92 (8.46)**	**1.76 (3.69)**	**80.00**	**16.01 (26.21)**	**6.13 (9.61)**	**38.00**	**13.63 (9.63)**

	Medium: MIK ($n = 413,\ m = 346$)			Medium: Corlat ($n = 466,\ m = 486$)			Hard: Load Balancing ($n = 61000,\ m = 64304$)		
Method	Time(s) ↓	PD integral ↓	Improvement ↑ (PD integral, %)	Time(s) ↓	PD integral ↓	Improvement ↑ (PD integral, %)	Time(s) ↓	PD integral ↓	Improvement ↑ (PD integral, %)
NoCuts	300.01 (0.009)	2355.87 (996.08)	NA	103.30 (128.14)	2818.40 (5908.31)	NA	300.00 (0.12)	14853.77 (951.42)	NA
Default	179.62 (122.36)	844.40 (924.30)	64.10	75.20 (120.30)	2412.09 (5892.88)	14.40	300.00 (0.06)	9589.19 (1012.95)	35.40
Random	289.86 (28.90)	2036.80 (933.17)	13.50	84.18 (124.34)	2501.98 (6031.43)	11.20	300.00 (0.09)	13621.20 (1162.02)	8.30
NV	299.76 (1.32)	2542.67 (529.49)	-7.90	90.26 (128.33)	3075.70 (7029.55)	-9.10	300.00 (0.05)	13933.88 (971.10)	6.20
Eff	298.48 (5.84)	2416.57 (642.41)	-2.60	104.38 (131.61)	3155.03 (7039.99)	-11.90	300.00 (0.07)	13913.07 (969.95)	6.30
SBP	286.07 (41.81)	2053.30 (740.11)	12.80	70.41 (122.17)	2023.87 (5085.96)	28.20	300.00 (0.10)	12535.30 (741.43)	15.60
HEM(Ours)	**176.12 (125.18)**	**785.04 (790.38)**	**66.70**	**58.31 (110.51)**	**1079.99 (2653.14)**	**61.68**	**300.00 (0.04)**	**9496.42 (1018.35)**	**36.10**

	Hard: Anonymous ($n = 37881,\ m = 49603$)			Hard: MIPLIB mixed neos ($n = 6958,\ m = 5660$)			Hard: MIPLIB mixed supportcase ($n = 19766,\ m = 19910$)		
Method	Time(s) ↓	PD integral ↓	Improvement ↑ (PD integral, %)	Time(s) ↓	PD integral ↓	Improvement ↑ (PD integral, %)	Time(s) ↓	PD integral ↓	Improvement ↑ (PD integral, %)
NoCuts	246.22 (94.90)	18297.30 (9769.42)	NA	253.65 (80.29)	14652.29 (12523.37)	NA	170.00 (131.60)	9927.96 (11334.07)	NA
Default	244.02 (97.72)	17407.01 (9736.19)	4.90	256.58 (76.05)	14444.05 (12347.09)	1.42	164.61 (135.82)	9672.34 (10668.24)	2.57
Random	243.49 (98.21)	16850.89 (10227.87)	7.80	255.88 (76.65)	14006.48 (12698.76)	4.41	165.88 (134.40)	10034.70 (11052.73)	-1.07
NV	242.01 (98.68)	16873.66 (9711.16)	7.80	263.81 (64.10)	14379.05 (12306.35)	1.86	**161.67 (131.43)**	8967.00 (9690.30)	9.68
Eff	244.94 (93.47)	17137.87 (9456.34)	6.30	260.53 (68.54)	14021.74 (12859.41)	4.30	167.35 (134.99)	9941.55 (10943.48)	-0.14
SBP	245.71 (92.46)	18188.63 (9651.85)	0.59	256.48 (78.59)	13531.00 (12898.22)	7.65	165.61 (135.25)	7408.65 (7903.47)	25.37
HEM(Ours)	**241.68 (97.23)**	**16077.15 (9108.21)**	**12.10**	**248.66 (89.46)**	**8678.76 (12337.00)**	**40.77**	162.96 (138.21)	**6874.80 (6729.97)**	**30.75**

we also evaluate HEM with a much longer time limit of 3 hours. The results are given in Appendix F.5. We train HEM with ADAM (Kingma & Ba, 2014) using the PyTorch (Paszke et al., 2019) and MindSpore (Chen, 2021). We use a single machine that contains eight GPU devices (NVidia GeForce GTX 3090 Ti) and 32 Intel Gold 6246R CPUs. For simplicity, we split each dataset into the training and test sets without the valid set. We train our model on the training set, and select the model that achieves the best performance on the training set to evaluate on the test set. Please refer to Appendix E.3 for implementation details and hyperparameters of HEM.

Baselines. Our baselines include five widely-used human-designed cut selection rules and a state-of-the-art learning-based cut selection method. Cut selection rules include NoCuts, Random, Normalized Violation (NV), Efficacy (Eff), and Default. NoCuts does not add any cuts. Default denotes the default cut selection rule used in SCIP 8.0.0. For learning-based methods, we implement a variant of the state-of-the-art learning-based methods (Tang et al., 2020; Huang et al., 2022), namely score-based policy (SBP). Please see Appendix E.2 for implementation details of these baselines.

Evaluation metrics. We use two primary evaluation metrics, i.e., the average solving time (Time, lower is better), and the average primal-dual gap integral (PD integral, lower is better). We provide more results in terms of another two metrics, i.e., the average number of nodes and the average primal-dual gap, in Appendix F.2. Furthermore, to evaluate different cut selection strategies compared to pure branch-and-bound without cutting plane separation, we propose an *Improvement* metric. Specifically, we define the metric by $\text{Im}_M(\cdot) = \frac{M(\text{NoCuts}) - M(\cdot)}{M(\text{NoCuts})}$, where $M(\text{NoCuts})$ represents the performance of NoCuts, and $M(\cdot)$ represents a map from a method to its performance. The improvement metric represents the improvement of a given method compared to the NoCuts method. *We mainly focus on the Time metric on easy datasets*, as the solver can solve all instances to optimality within the time limit. However, HEM and baselines cannot solve all instances to optimality within the time limit on medium and hard datasets. As a result, the average solving time of those unsolved instances is the same, which makes it difficult to distinguish the performance of different cut selection methods using the Time metric. Therefore, *we mainly focus on the PD integral metric on medium and hard datasets*. Note that the PD integral is also a well-recognized metric for measuring the solver performance (Bowly et al., 2021; Cao et al., 2022).

#Experiment 1. Comparative evaluation (1) **Easy datasets.** HEM significantly outperforms the baselines on easy datasets, especially on Max Independent Set and Multiple Knapsack. HEM and SBP achieve better performance than all rule-based baselines, demonstrating that it is promising to enhance modern MILP solvers by learning cut selection. Compared to SBP, HEM improves the Time by 7.7% and 16.4% on Max Independent Set and Multiple Knapsack, respectively, which demonstrates the superiority of our method over learning-based baselines. (2) **Medium datasets.** On MIK

Table 2: Comparison between HEM and HEM without the higher-level model.

	Easy: Max Independent Set ($n = 500,\ m = 1953$)			Medium: Corlat ($n = 466,\ m = 486$)			Hard: MIPLIB mixed neos ($n = 6958,\ m = 5660$)		
Method	Time(s) ↓	Improvement ↑ (Time, %)	PD integral ↓	Time(s) ↓	PD integral ↓	Improvement ↑ (PD integral, %)	Time(s) ↓	PD integral ↓	Improvement ↑ (PD integral, %)
NoCuts	8.78 (6.66)	NA	71.31 (51.74)	103.30 (128.14)	2818.40 (5908.31)	NA	253.65 (80.29)	14652.29 (12523.37)	NA
Default	3.88 (5.04)	55.81	29.44 (35.27)	75.20 (120.30)	2412.09 (5892.88)	14.42	256.58 (76.05)	14444.05 (12347.09)	1.42
SBP	2.43 (5.55)	72.32	21.99 (40.86)	70.41 (122.17)	2023.87 (5085.96)	28.19	256.48 (78.59)	13531.00 (12898.22)	7.65
HEM w/o H	1.88 (4.20)	78.59	16.70 (28.15)	63.14 (115.26)	1939.08 (5484.83)	31.20	249.21 (88.09)	13614.29 (12914.76)	7.08
HEM (Ours)	**1.76 (3.69)**	**79.95**	**16.01 (26.21)**	**58.31 (110.51)**	**1079.99 (2653.14)**	**61.68**	**248.66 (89.46)**	**8678.76 (12337.00)**	**40.77**

Table 3: Comparison between HEM, HEM-ratio, and HEM-ratio-order.

	Easy: Max Independent Set ($n = 500,\ m = 1953$)			Medium: Corlat ($n = 466,\ m = 486$)			Hard: MIPLIB mixed neos ($n = 6958,\ m = 5660$)		
Method	Time(s) ↓	Improvement ↑ (Time, %)	PD integral ↓	Time(s) ↓	PD integral ↓	Improvement ↑ (PD integral, %)	Time(s) ↓	PD integral ↓	Improvement ↑ (PD integral, %)
NoCuts	8.78 (6.66)	NA	71.31 (51.74)	103.30 (128.14)	2818.40 (5908.31)	NA	253.65 (80.29)	14652.29 (12523.37)	NA
Default	3.88 (5.04)	55.81	29.44 (35.27)	75.20 (120.30)	2412.09 (5892.88)	14.42	256.58 (76.05)	14444.05 (12347.09)	1.42
SBP	2.43 (5.55)	72.32	21.99 (40.86)	70.41 (122.17)	2023.87 (5085.96)	28.19	256.48 (78.59)	13531.00 (12898.22)	7.65
HEM-ratio-order	2.30 (5.18)	73.80	21.19 (38.52)	70.94 (122.93)	1416.66 (3380.10)	49.74	245.99 (93.67)	14026.75 (12683.60)	4.27
HEM-ratio	2.26 (5.06)	74.26	20.82 (37.81)	67.27 (117.01)	1251.60 (2869.87)	55.59	**244.87 (95.56)**	13659.93 (12900.59)	6.77
HEM (Ours)	**1.76 (3.69)**	**79.95**	**16.01 (26.21)**	**58.31 (110.51)**	**1079.99 (2653.14)**	**61.68**	248.66 (89.46)	**8678.76 (12337.00)**	**40.77**

and CORLAT, HEM still outperforms the baselines. Especially on CORLAT, HEM achieves at least 33.48% improvement in terms of the PD integral compared to the baselines. (3) **Hard datasets.** HEM significantly outperforms the baselines in terms of the PD integral on several problems in hard datasets. We emphasize that HEM achieves outstanding performance on two challenging benchmarks from MIPLIB 2017 and challenging real-world problems (Load Balancing and Anonymous), highlighting the potential of applying HEM to large-scale real-world applications. Moreover, SBP performs extremely poor on several medium and hard datasets, which implies that it can be difficult to learn good cut selection policies on challenging MILP problems.

#Experiment 2. Ablation study We present ablation studies of HEM on Max Independent Set, CORLAT, and MIPLIB mixed neos, which are representative datasets from the easy, medium, and hard datasets, respectively. We provide additional results on more datasets in Appendix F.3.

Contribution of each component. First, we perform ablation studies to understand the contribution of each individual component in HEM. HEM contains two components: the lower-level model and the higher-level model. We report the performance of HEM and HEM without the higher-level model (HEM w/o H) in Table 2. HEM w/o H is essentially a pointer network. Note that it can still implicitly predicts the number of cuts that should be selected by predicting an end token as used in language tasks (Sutskever et al., 2014). Please see Appendix E.5 for details. The results in Table 2 show that HEM w/o H outperforms all baselines in terms of all metrics on Max Independent Set and CORLAT, which demonstrates the advantages of formulating the cut selection task as a sequence to sequence learning problem. Although HEM w/o H outperforms Default on MIPLIB mixed neos, HEM w/o H performs on par with SBP. A possible reason is that the cardinality of the action space is large, which makes it difficult for the sequence model to explore the action space efficiently. Therefore, HEM w/o H tends to be trapped to local optimal. Furthermore, the results in Table 2 show that HEM significantly outperforms HEM w/o H and baselines on three datasets, demonstrating the effectiveness of the higher-level model for efficient exploration in complex tasks.

The importance of tackling (P1)-(P3)[1]. Second, we perform ablation studies to understand the importance of tackling **(P1)-(P3)** in cut selection. (1) **HEM.** HEM tackles **(P1)-(P3)** in cut selection simultaneously. (2) **HEM-ratio.** In order not to learn how many cuts should be selected, we remove the higher-level model of HEM and *force the lower-level model to select a fixed ratio of cuts*. We denote it by HEM-ratio. Note that HEM-ratio is different from HEM w/o H (see Appendix E.5). HEM-ratio tackles **(P1)** and **(P3)** in cut selection. (3) **HEM-ratio-order.** To further mute the effect of the order of selected cuts, we reorder the selected cuts given by HEM-ratio with the original index of the generated cuts, which we denote by HEM-ratio-order. HEM-ratio-order mainly tackles **(P1)** in cut selection. The results in Table 3 suggest the following. HEM-ratio-order significantly outperforms Default and NoCuts, demonstrating that tackling **(P1)** by data-driven methods is crucial. HEM significantly outperforms HEM-ratio in terms of the PD integral, demonstrating the significance of tackling **(P2)**. HEM-ratio outperforms HEM-ratio-order in terms of the Time and the PD integral, which demonstrates the importance of tackling **(P3)**. Moreover, HEM-ratio and HEM-ratio-order perform better than SBP on Max Independent Set and CORLAT, demonstrating the advantages of using sequence model to learn cut selection over SBP. HEM-ratio and HEM-ratio-order perform on par with SBP on MIPLIB mixed neos. We provide possible reasons in Appendix F.3.

[1] **(P1)-(P3)** denote three problems in cut selection. **(P1)** denotes which cuts should be preferred. **(P2)** denotes how many cuts should be selected. **(P3)** denotes what order of selected cuts should be preferred.

Table 4: **Left**: The generalization ability of HEM. **Right**: Test on Production Planning problems.

	Max Independent Set ($n = 1000,\ m = 3946,\ 4\times$)			Max Independent Set ($n = 5940,\ m = 1500,\ 9\times$)		
Method	Time(s) ↓	Improvement ↑ (time, %)	PD integral ↓	Time(s) ↓	Improvement ↑ (time, %)	PD integral ↓
NoCuts	170.06 (100.61)	NA	874.45 (522.29)	300.00 (0)	NA	2019.93 (353.27)
Default	42.40 (76.00)	48.72	198.61 (331.20)	111.18 (144.13)	60.91	616.46 (798.94)
Random	118.25 (109.05)	-43.00	574.33 (516.11)	245.13 (115.80)	13.82	1562.20 (793.09)
NV	160.30 (101.41)	-93.86	784.98 (493.24)	299.97 (0.49)	-5.46	1922.52 (349.67)
Eff	158.75 (100.40)	-91.98	779.63 (493.05)	299.45 (3.77)	-5.28	1921.61 (361.26)
SBP	50.55 (89.14)	38.87	253.81 (426.94)	108.42 (143.68)	61.88	680.41 (903.88)
HEM (Ours)	**35.34 (67.91)**	**57.26**	**160.56 (282.03)**	**108.02 (143.02)**	**62.02**	**570.48 (760.65)**

	Production Planning ($n = 3582.25,\ m = 5040.42$)			
Method	Time (s) ↓	Improvement (Time, %) ↑	PD integral ↓	Improvement ↑ (PD integral, %)
NoCuts	278.79 (231.02)	NA	17866.01 (21309.85)	NA
Default	296.12 (246.25)	-6.22	17703.39 (21330.40)	0.91
Random	280.18 (237.09)	-0.50	18120.21 (21660.01)	-1.42
NV	259.48 (227.81)	6.93	17295.18 (21860.07)	3.20
Eff	263.60 (229.24)	5.45	16636.52 (21322.89)	6.88
SBP	276.61 (235.84)	0.78	16952.85 (21386.07)	5.11
HEM (Ours)	**241.77 (229.97)**	**13.28**	**15751.08 (20683.53)**	**11.84**

#Experiment 3. Generalization We evaluate the ability of HEM to generalize across different sizes of MILPs. Let $n \times m$ denotes the size of MILP instances. Following (Gasse et al., 2019; Sun et al., 2020), we test the generalization ability of HEM on Set Covering and Max Independent Set, as we can artificially generate instances with arbitrary sizes for synthetic MILP problems. On Max Independent Set, we test HEM on four times and nine times larger instances than seen during training. The results in Table 4 (Left) show that HEM generalizes well to instances that are significantly larger than seen during training. In particular, HEM significantly outperforms all baselines in terms of the Time on $4\times$ Max Independent Set. Moreover, HEM consistently outperforms SBP in terms of the Time and PD integral, demonstrating the superiority of HEM. Interestingly, SBP also generalizes well to large instances, highlighting the potential for good generalization by learning cut selection.

#Experiment 4. Visualization of selected cuts To evaluate whether HEM can select cuts that complement each other nicely, we visualize the cuts selected by HEM-ratio and SBP on a randomly sampled instance from Max Independent Set and CORLAT, respectively. We evaluate HEM-ratio instead of HEM as HEM-ratio selects the same number of cuts as SBP. Specifically, we perform principal component analysis (Mohri et al., 2018) on selected cuts to reduce the cut features to two-dimensional space as shown in Figure 3. Colored points illustrate reduced cut features. To visualize the diversity of selected cuts, we use dashed lines to connect the points with the smallest and largest x,y coordinates. That is, the area covered by the dashed lines represents the diversity of selected cuts. The results show that SBP tends to select many similar cuts that are possibly redundant, especially on Max Independent Set. In contrast, HEM-ratio selects much more diverse cuts than SBP, which demonstrates that HEM tends to select cuts that complement each other nicely. Please refer to Appendix F.4 for results on more datasets.

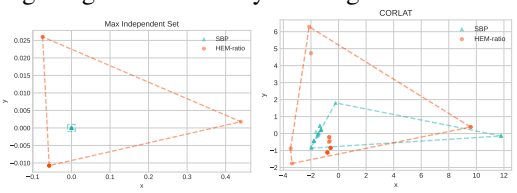


Figure 3: We perform principal component analysis on cuts selected by HEM-ratio and SBP. Each colored point illustrates a reduced cut feature. To visualize the diversity of selected cuts, we use dashed lines to connect the points with the smallest and largest x,y coordinates.

#Experiment 5. Deployment in real-world production planning problems To further evaluate the effectiveness of our proposed HEM, we deploy HEM to real-world production planning problems at an anonymous enterprise, which is one of the largest global commercial technology enterprise. Please refer to Appendix D.3 for more details of the problems. The results in Table 4 (Right) show that HEM significantly outperforms all baselines in terms of the Time and PD integral. Specifically, HEM improves the Time by 13.28%, 19.5%, and 12.5% compared to NoCuts, Default, and SBP, respectively. HEM improves the PD integral by 11.84%, 10.93%, and 6.73% compared to NoCuts, Default, and SBP, respectively. The results highlight the ability to improve the efficiency of modern MILP solvers with our proposed HEM in large-scale real-world applications. Interestingly, Default performs poorer than NoCuts, which implies that an improper cut selection policy could significantly degrade the efficiency of MILP solvers.

6 Conclusion

In this paper, we first observe from extensive empirical results that the order of selected cuts has a large impact on the efficiency of solving MILPs as well. We then propose a novel **h**ierarchical s**e**quence **m**odel (HEM) to learn cut selection policies via reinforcement learning. Specifically, HEM consists of a two-level model: (1) a higher-level model aims to learn how many cuts should be selected, (2) and a lower-level model formulates the cut selection task as a sequence to sequence learning problem to learn to select an ordered subset with the size determined by the higher-level model. Experiments show that HEM significantly improves the efficiency of solving MILPs compared to human-designed and learning-based baselines on both synthetic and large-scale real-world MILPs. We believe that our proposed approach will bring new insights into learning cut selection.

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A PROOF

A.1 PROOF OF PROPOSITION 1

Proposition 2. *Given the cut selection policy* $\pi_\theta(a_k|s) = \mathbb{E}_{k\sim\pi^h_{\theta_1}(\cdot|s)}[\pi^l_{\theta_2}(a_k|s,k)]$ *and the training objective (3), the hierarchical policy gradient takes the form of*

$$\nabla_{\theta_1} J([\theta_1,\theta_2]) = \mathbb{E}_{s\sim\mu,k\sim\pi^h_{\theta_1}}[\nabla_{\theta_1}\log(\pi^h_{\theta_1}(k|s))\mathbb{E}_{a_k\sim\pi^l_{\theta_2}(\cdot|s,k)}[r(s,a_k)]]$$
$$\nabla_{\theta_2} J([\theta_1,\theta_2]) = \mathbb{E}_{s\sim\mu,k\sim\pi^h_{\theta_1}(\cdot|s),a_k\sim\pi^l_{\theta_2}(\cdot|s,k)}[\nabla_{\theta_2}\log\pi^l_{\theta_2}(a_k|s,k)r(s,a_k)]$$

Proof. The optimization objective takes the form of

$$\begin{aligned}J(\theta) &= \mathbb{E}_{s\sim\mu,a_k\sim\pi_\theta(\cdot|s)}[r(s,a_k)]\\ &= \mathbb{E}_{s\sim\mu}[\sum_{a_k}\int_{k=0}^1 \pi^h_{\theta_1}(k|s)\pi^l_{\theta_2}(a_k|s,k)r(s,a_k)dk]\\ &= \mathbb{E}_{s\sim\mu}[\int_{k=0}^1\sum_{a_k}\pi^h_{\theta_1}(k|s)\pi^l_{\theta_2}(a_k|s,k)r(s,a_k)dk],\end{aligned}$$

where $\theta = [\theta_1,\theta_2]$ with $[\theta_1,\theta_2]$ denoting the concatenation of the two vectors, $\pi_\theta(a_k|s) = \mathbb{E}_{k\sim\pi^h_{\theta_1}(\cdot|s)}[\pi^h_{\theta_2}(a_k|s,k)]$, and μ denotes the initial state distribution.

We first compute the policy gradient for θ_1:

$$\begin{aligned}&\nabla_{\theta_1} J([\theta_1,\theta_2])\\ =&\nabla_{\theta_1}(\mathbb{E}_{s\sim\mu}[\int_{k=0}^1\sum_{a_k}\pi^h_{\theta_1}(k|s)\pi^l_{\theta_2}(a_k|s,k)r(s,a_k)dk])\\ =&\mathbb{E}_{s\sim\mu}[\nabla_{\theta_1}[\int_{k=0}^1\pi^h_{\theta_1}(k|s)\sum_{a_k}\pi^l_{\theta_2}(a_k|s,k)r(s,a_k)dk]].\end{aligned}$$

Let

$$\begin{aligned}r^h(s,k,\theta_2) &= \sum_{a_k}\pi^l_{\theta_2}(a_k|s,k)r(s,a_k)\\ &= \mathbb{E}_{a_k\sim\pi^l_{\theta_2}(\cdot|s,k)}[r(s,a_k)],\end{aligned}$$

then we have that

$$\begin{aligned}\nabla_{\theta_1} J([\theta_1,\theta_2]) &= \mathbb{E}_{s\sim\mu}[\nabla_{\theta_1}[\int_{k=0}^1\pi^h_{\theta_1}(k|s)r(s,k,\theta_2)dk]]\\ &= \mathbb{E}_{s\sim\mu,k\sim\pi^h_{\theta_1}(\cdot|s)}[\nabla_{\theta_1}\log\pi^h_{\theta_1}(k|s)r(s,k,\theta_2)].\end{aligned}$$

Therefore, we have that

$$\begin{aligned}&\nabla_{\theta_1} J([\theta_1,\theta_2])\\ &= \mathbb{E}_{s\sim\mu,k\sim\pi^h_{\theta_1}(\cdot|s)}[\nabla_{\theta_1}\log(\pi^h_{\theta_1}(k|s))\mathbb{E}_{a_k\sim\pi^l_{\theta_2}(\cdot|s,k)}[r(s,a_k)]].\end{aligned}$$

We then compute the policy gradient for θ_2:

$$\begin{aligned}&\nabla_{\theta_2} J([\theta_1,\theta_2])\\ =&\nabla_{\theta_2}(\mathbb{E}_{s\sim\mu}[\int_{k=0}^1\sum_{a_k}\pi^h_{\theta_1}(k|s)\pi^l_{\theta_2}(a_k|s,k)r(s,a_k)dk])\\ =&\mathbb{E}_{s\sim\mu,k\sim\pi^h_{\theta_1}(\cdot|s)}[\nabla_{\theta_2}[\sum_{a_k}\pi^l_{\theta_2}(a_k|s,k)r(s,a_k)]]\\ =&\mathbb{E}_{s\sim\mu,k\sim\pi^h_{\theta_1}(\cdot|s),a_k\sim\pi^l_{\theta_2}(\cdot|s,k)}[\nabla_{\theta_2}\log\pi^l_{\theta_2}(a_k|s,k)r(s,a_k)],\end{aligned}$$

which completes the proof. □

B RELATED WORK

B.1 MACHINE LEARNING FOR MILP

The use of machine learning methods to help improve the MILP solver performance has been an active topic of significant interest in recent years (Bengio et al., 2021; Lodi & Zarpellon, 2017; Bowly et al., 2021; Gasse et al., 2019). During the solving process of the solvers, many crucial decisions that significantly impact the solver performance are based on heuristics (Achterberg, 2007). Recent methods propose to replace these hand-crafted heuristics with machine learning models (Bengio et al., 2021). This line of research has shown significant improvement on the solver performance, including cut selection (Tang et al., 2020; Paulus et al., 2022; Turner et al., 2022; Baltean-Lugojan et al., 2019), variable selection (Khalil et al., 2016; Gasse et al., 2019; Balcan et al., 2018; Zarpellon et al., 2021), node selection (He et al., 2014; Sabharwal et al., 2012), column generation (Morabit et al., 2021), and primal heuristics selection (Khalil et al., 2017; Hendel et al., 2019). In this paper, we focus on cut selection, which plays a significant role in modern MILP solvers (Dey & Molinaro, 2018a; Tang et al., 2020).

For cut selection, many existing learning-based methods (Tang et al., 2020; Paulus et al., 2022; Huang et al., 2022) focus on learning which cuts should be preferred by learning a scoring function to measure cut quality. Specifically, (Tang et al., 2020) proposes a reinforcement learning approach to learn to score Gomory cuts (Gomory, 1960) and select a Gomory cut with the best scores. Furthermore, (Paulus et al., 2022) designs a lookahead selection rule which selects a cut that yield the best dual bound improvement, and proposes to learn the expert rule via imitation learning. Instead of selecting the best cut, (Huang et al., 2022) frames cut selection as multiple instance learning to learn a scoring function and selects a fixed ratio of cuts with high scores. However, they neglect the importance of learning how many cuts should be selected. Moreover, we empirically show that the *order of selected cuts* has a large impact on the efficiency of solving MILPs (see Section 3).

Moreover, (Turner et al., 2022) proposes to learn the weightings of four existing scoring rules designed by experts. For the theoretical analysis, (Balcan et al., 2021) provides some provable guarantees for learning cut selection policies.

B.2 SEQUENCE MODEL

Sequence model such as long-short term memory and Transformer has achieved outstanding performance in language tasks such as machine translation (Hochreiter & Schmidhuber, 1997; Sutskever et al., 2014; Vaswani et al., 2017). For combinatorial optimization, recent works (Vinyals et al., 2015; Bello* et al., 2017) propose a variant of the traditional sequence model, namely pointer network, which is applied to directly finding solutions for specific combinatorial optimization problems, such as the Travelling Salesman Problem (Lenstra & Shmoys, 2009). Instead of finding solutions directly, we propose to use the pointer network for cut selection in modern MILP solvers. To the best of our knowledge, we are the first to apply the pointer network to cut selection, which not only captures the order of selected cuts, but also can well capture the interaction among cuts to select cuts that complement each other nicely.

C MORE DETAILS OF BACKGROUND

C.1 MORE DETAILS OF THE PRIMAL-DUAL GAP INTEGRAL

We keep track of two important bounds when running branch-and-cut, including the global primal and dual bound. The global primal bound corresponds to the value of the best feasible solution found so far, which is the best upper bound of the problem in (1). The global dual bound corresponds to the minimum dual bound across all leaves of the search tree, which is the best lower bound of the problem in (1). We define the *primal-dual gap integral* by the area between the curve of the solver's global primal bound and the curve of the solver's global dual bound. With a time limit T, we define the primal-dual gap integral by

$$\int_{t=0}^{T} (\mathbf{c}^T \mathbf{x}_t^* - \mathbf{z}_t^*) \mathrm{d}t,$$

where $\mathbf{c}$ is the objective coefficient vector as in (1), $\mathbf{x}_t^*$ is the best feasible solution found at time t, $\mathbf{z}_t^*$ is the best dual bound at time t. We define the *primal-dual gap* by the difference between the global primal bound and the global dual bound. In SCIP 8.0.0 (Bestuzheva et al., 2021), the initial value of the primal-dual gap is set to a constant 100. The primal-dual gap integral is a well-recognized metric for measuring the solver performance. For example, the primal-dual gal integral is set as a primary evaluation metric in the NeurIPS 2021 ML4CO competition (Bowly et al., 2021).

D DETAILS OF DATASETS USED IN THIS PAPER

D.1 DATASETS USED IN THE MAIN EVALUATION

Easy datasets. Easy datasets consist of Set Covering, Max Independent Set, and Multiple Knapsack. We artificially generate the synthetic MILP problems following (Gasse et al., 2019; Scavuzzo et al., 2022). Specifically, readers can refer to `https://github.com/ds4dm/learn2branch` or `https://github.com/lascavana/rl2branch` for code to generate the easy datasets. We will also release our code once the paper is accepted to be published.

Medium datasets. Medium datasets consist of MIK (He et al., 2014) and CORLAT (Nair et al., 2020). Readers can refer to `https://atamturk.ieor.berkeley.edu/data/mixed.integer.knapsack/` for MIK. Readers can refer to `https://bitbucket.org/mlindauer/aclib2/src/master/` for CORLAT.

Hard datasets. (1) Benchmarks from MIPLIB 2017. Note that MIPLIB 2017 (MIPLIB) (Gleixner et al., 2021) contains instances of MILPs across many different application areas and has been used as a long-standing standard benchmark for MILP solvers (Nair et al., 2020; Turner et al., 2022; Gleixner et al., 2021). Previous work (Turner et al., 2022) has shown that directly learning over the full MIPLIB can be extremely challenging, as these instances are heterogeneous but machine learning has difficulty in learning from heterogeneous datasets. Despite this challenge, we take the first step towards learning over subsets of MIPLIB. Specifically, we construct two subsets by selecting similar instances from MIPLIB. We measure the similarity between instances by 100 human-designed instance features (Gleixner et al., 2021). Following (Turner et al., 2022), we first discard instances from MILLIB that satisfy any of the criteria in Table 5. This ensures that a good cut selection strategy can significantly improve the dual bound on the remaining instances. Note that we only use three of seven criteria that are used in (Turner et al., 2022) to preserve as many instances as possible.

Table 5: Criteria for removing instances from MIPLIB 2017.

Criteria	% of instances removed
Tags: *feasibility*, *numerics*, *infeasible*, *no solution*	4.5%, 17.4%, 2.8%, 0.9%
Presolve longer than 300 seconds under default conditions	4.8%
Solved to optimality at root	9.9%

To select similar instances from MIPLIB 2017, we first choose a representative instance that has knapsack constraints (neos-1456979), and a representative instance that has set covering constraints (supportcase40). Then we construct the dataset MIPLIB mixed neos following the procedure in Algorithm xx. Furthermore, we construct the dataset MIPLIB mixed supportcase by selecting instances following the procedure in Algorithm xx. Note that We measure the similarity between instances by 100 human-designed instance features (Gleixner et al., 2021).

Specifically, MIPLIB mixed neos contains 20 instances: neos-1456979, ic97_tension, icir97_tension, l2p12, lectsched-4-obj, lectsched-5-obj, loopha13, neos-686190, neos-2294525-abba, neos-3009394-lami, neos-3046601-motu, neos-3046615-murg, neos-3610173-itata, neos-4338804-snowy, neos-5221106-oparau, neos-5260764-orauea, neos-5261882-treska, neos-5266653-tugela, neos16, and timtab1CUTS.

Moreover, MIPLIB mixed supportcase contains 40 instances: supportcase40, 30_70_45_05_100, 30_70_45_095_100, acc-tight2, acc-tight4, acc-tight5, comp07-2idx, comp08-2idx, comp12-2idx, comp21-2idx, decomp1, decomp2, gus-sch, istanbul-no-cutoff, mkc, mkc1, neos-555343, neos-555424, neos-738098, neos-872648, neos-933562, neos-933638, neos-933966, neos-935234, neos-935769, neos-983171, neos-1330346, neos-1337307, neos-1396125, neos-3209462-rhin, neos-3755335-nizao, neos-3759587-noosa, neos-4300652-rahue, neos18, physicianshed6-1, physicianshed6-2, piperout-d27, qiu, reblock354, and supportcase37.

Algorithm 1 Pseudo code for constructing MIPLIB datasets.

Initialize Hierarchical sequence model $\pi_{[\theta_1,\theta_2]}$, MILP instances $\mathcal{D}$, training dataset $\mathcal{D}_{\text{train}}$, batch size N_b, training epochs N_e, policy learning rate α
for N_e epochs **do**
  Empty the training dataset $\mathcal{D}_{\text{train}}$
  for N_b steps **do**
    Randomly sample a MILP s_0 from $\mathcal{D}$
    Take action k and a_k at state s_0 with the policy π
    Receive reward r and add (s_0, k, a_k, r) to $\mathcal{D}_{\text{train}}$
  end for
  Compute hierarchical policy gradient using $\mathcal{D}_{\text{train}}$ as in proposition 1
  Update the parameters, $\theta_1 = \theta_1 + \alpha \nabla_{\theta_1} J([\theta_1, \theta_2])$, $\theta_2 = \theta_2 + \alpha \nabla_{\theta_2} J([\theta_1, \theta_2])$
end for

(2) Benchmarks used in NeurIPS 2021 ML4CO competition The Load Balancing and Anonymous problems used in the main text are from the NeurIPS 2021 ML4CO competition (Bowly et al., 2021). Readers can refer to `https://www.ecole.ai/2021/ml4co-competition/` for details of the competition. The competition releases three challenging datasets, but we only use two of the three datasets. The major reason is that the average number of the candidate cuts on instances from the third dataset (Item Placement) is less than five, which makes cut selection has little impact on the overall solver performance.

D.2 Datasets used in Section: Motivating results

(1) In Figure 1a in the main text, we use five datasets, namely D1, D2, D3, D4, and D5, respectively. Specifically, D1 represents MIPLIB mixed supportcase, D2 represents the single instance neos-1456979 from MIPLIB 2017, D3 represents MIPLIB mixed neos, D4 represents Anonymous, and D5 represents the single instance lectsched-5-obj from MIPLIB 2017. (2) In Figure 1b in the main text, we use the dataset MIPLIB mixed neos.

D.3 Real-world supply chain problems

The supply chain problem aims to find the optimal production planning for hundreds of factories according to the daily order demand. The constraints include the production capacity for each production line in each factory, transportation limit, the order rate, etc. The optimization objective is to minimize the production cost and lead time simultaneously. We split the dataset into training and test sets with 80% and 20% of the instances. To promote the community of machine learning for MILP, we will release the dataset once the paper is accepted to be published.

E Algorithm implementation and experimental settings

E.1 Designed cut features

Following (Huang et al., 2022; Wesselmann & Stuhl, 2012; Dey & Molinaro, 2018b; Achterberg, 2007), we design 13 cut features for the cut selection task, such as the extent to which a cut is violated by the current LP solution and the proportion of non-zero coefficients of a cut. We present a detailed description of the designed cut features in Table 6. We emphasize that we do not tune the cut features. Therefore, it is promising to further improve our proposed method by design better cut features or using graph neural network to learn better features in the future work.

Table 6: The designed cut features of a generated cut $\boldsymbol{\alpha}^T \mathbf{x} \leq \beta$. (Suppose $\mathbf{c}$ denotes the objective coefficient.)

Feature	Description	Number
cut coefficients	the mean, max, min, std of cut coefficients	4
objective coefficients	the mean, max, min, std of the objective coefficients	4
parallelism	the parallelism between the objective and the cut $\frac{\boldsymbol{c}^T \boldsymbol{\alpha}}{\|\boldsymbol{c}\|\|\boldsymbol{\alpha}\|}$	1
efficacy	the Euclidean distance of the cut hyperplane to the current LP solution	1
support	the proportion of non-zero coefficients of the cut	1
integral support	the proportion of non-zero coefficients with respect to integer variables of the cut	1
normalized violation	the violation of the cut to the current LP solution $\max\{0, \frac{\boldsymbol{\alpha}^T \mathbf{x}_{LP} - \beta}{\|\beta\|}\}$	1

E.2 IMPLEMENTATION DETAILS OF BASELINES

In this part, we present a detailed description of all baselines used in this paper. We denote a cut by $\boldsymbol{\alpha}^T \mathbf{x} \leq \beta$ and the current LP solution by $\mathbf{x}^*$. Throughout all experiments, we set the ratio of selected cuts 0.2 for all score-based rules and learning baselines.

Random Random selects a fixed ratio of candidate cuts stochastically.

Normalized Violation (NV) NV is a score-based rule. It score each cut based on the normalized violation of the cut to the current LP solution, and select a ratio of 0.2 cuts with high scores. The normalized violation is defined by $\max\{0, \frac{\boldsymbol{\alpha}^T \mathbf{x}^*_{\text{LP}} - \beta}{|\beta|}\}$.

Efficacy (Eff) Eff is a score-based rule. It score each cut based on the Euclidean distance of the cut hyperplane to the current LP solution, and select a ratio of 0.2 cuts with high scores.

Default Default is the default cut selection rule used in SCIP 8.0.0 (Bestuzheva et al., 2021). Please refer to (Achterberg, 2007) for a detailed description of the SCIP's default cut selection rule. Noet that Default tackles the two problems: (1) which cuts should be preferred, and (2) how many cuts should be selected, in cut selection by human-designed heuristics.

Score-based policy (SBP) Since the state-of-the-art (SOTA) reinforcement learning based methods for cut selection (Tang et al., 2020) is deigned for the setting that selects a best cut in each round, we implement a variant of the SOTA to adapt to our setting that selects a subset of cuts in each round, namely SBP. Specifically, the core idea of SBP is learning a scoring function to measure cut quality as well. For a fair comparison, SBP uses the same cut features as HEM and we train SBP via reinforcement learning as well. We implement the scoring function with a multi-layer perceptron that predicts the score of a given cut. That is, the scoring function predicts a cut's score based on the features of the cut. Moreover, we train the scoring function via evolutionary strategies as (Tang et al., 2020).

E.3 IMPLEMENTATION DETAILS AND HYPERPARAMETERS OF HEM

E.3.1 REWARD FUNCTION

For easy datasets, we set the reward as the negative solving time. For medium and hard datasets, we set the reward as the negative primal-dual gap integral within a time limit 300 seconds.

For the real-world production planning problems, we set the reward as the negative primal-dual gap integral within a time limit 600 seconds or the negative dual bound improvement. The results of HEM reported in the main text are based on the negative dual bound improvement reward. We provide the results of HEM that uses the negative primal-dual gap integral in Table xx.

We emphasize that we can set the reward according to our objective in real-world problems. For example, suppose we aim to minimize the primal-dual gap within a time limit, then we can set the reward as the primal-dual gap within the time limit.

E.3.2 POLICY NETWORK ARCHITECTURE

The higher-level model contains a LSTM encoder and a MLP. The LSTM network encodes variable sized inputs into hidden vector with dimension 128. The MLP network cantains two hidden layers with 128 units. The lower-level model is essentially a pointer network. We keep the hyperparameters of the pointer network as that used in (Bello* et al., 2017).

E.3.3 OPTIMIZATION

Throughout all experiments, we apply Adam optimizer with learning rate $\alpha_1 = 1e-4$ to optimize the lower-level model, and learning rate $\alpha_2 = 5e-4$ to optimize the higher-level model. For each epoch, we collect 32 samples for training, and we set the total epochs 100. It is interesting that learning a good cut selection strategy does not need too much data as shown in (Tang et al., 2020).

For training stability, we delay the higher-level policy update. This creares a two-timescale algorithm, as often required for convergence in the linear setting (Fujimoto et al., 2018; Konda &

Algorithm 2 Pseudo code for training the HEM

Initialize Hierarchical sequence model $\pi_{[\theta_1,\theta_2]}$, MILP instances $\mathcal{D}$, training dataset $\mathcal{D}_{\text{train}}$, batch size N_b, training epochs N_e, policy learning rate α
for N_e epochs **do**
  Empty the training dataset $\mathcal{D}_{\text{train}}$
  for N_b steps **do**
    Randomly sample a MILP s_0 from $\mathcal{D}$
    Take action k and a_k at state s_0 with the policy π
    Receive reward r and add (s_0, k, a_k, r) to $\mathcal{D}_{\text{train}}$
  end for
  Compute hierarchical policy gradient using $\mathcal{D}_{\text{train}}$ as in proposition 1
  Update the parameters, $\theta_1 = \theta_1 + \alpha \nabla_{\theta_1} J([\theta_1, \theta_2])$, $\theta_2 = \theta_2 + \alpha \nabla_{\theta_2} J([\theta_1, \theta_2])$
end for

Tsitsiklis, 2003). We set the delay freq 2. That is, we first train the lower-level policy twice, then train the higher-level policy once.

E.4 Details of the pointer network

The pointer network is first introduced by (Vinyals et al., 2015) for directly finding solutions of specific combinatorial optimization problems, such as Travelling Salesman Problems. The pointer network consists of a Long Short-Term Memory encoder, a Long Short-Term Memory decoder, and an attention that is used as a pointer to select a member of the input sequence as the output (Vinyals et al., 2015). Specifically, we implement the pointer network following (Bello* et al., 2017). Please refer to (Bello* et al., 2017) for implementation details of the pointer network.

The major difference between our used pointer network and the pointer network used in (Bello* et al., 2017) is that we use the pointer network to select ordered subsets of input sequences, but (Bello* et al., 2017) use the pointer network to output permutations of input sequences.

E.5 Difference between HEM-ratio and HEM w/o H

The policy network of HEM-ratio and HEM w/o H are both essentially a pointer network (Vinyals et al., 2015), a variant of the sequence model. We present the major difference between HEM-ratio and HEM w/o H in the following. HEM w/o H predicts an end token as used in language tasks (Sutskever et al., 2014; Vaswani et al., 2017) to implicitly determine the number of cuts that should be selected. In contrast, HEM-ratio always selects a fixed ratio of cuts, i.e, it always ends decoding at a pre-determined position. Therefore, HEM w/o H can learn how many cuts should be selected, but HEM-ratio cannot.

Details of HEM w/o H To implement HEM w/o H, we augment each input sequence with an end token, i.e., a thirteen dimensional tensor with values all being one. The end token is at the end position of the input sequence. Once the decoder of HEM w/o H outputs the end token, then the decoding ends. That is, HEM w/o H can implicitly predicting the number of cuts that should be selected by predicting whether to decode the end token at current decoding step.

E.6 The training algorithm

We provide the procedure of the training algorithm of HEM in Table 2.

E.7 Discussion of HEM

In this part, we provide details of some additional advantages of HEM. (1) Inspired by hierarchical reinforcement learning (Sutton et al., 1999b; Nachum et al., 2018), HEM leverages the hierarchical structure of the cut selection task, which is important for efficient exploration in complex decision-making tasks. (2) Previous methods (Tang et al., 2020; Huang et al., 2022) usually train cut selection policies via black-box optimization methods such as evolution strategies (Salimans et al., 2017). In contrast, HEM is differentiable and we train the HEM via gradient-based algorithms, which is more sample efficient than black-box optimization methods (Sutton & Barto, 2018; Schulman et al., 2015).

Table 7: Policy evaluation on easy, medium, and hard datasets in terms of the total number of nodes and the primal-dual gap. The best performance are marked in bold.

	Set Covering		Max Independent Set		Multiple Knapsack	
Method	Nodes	PD gap	Nodes	PD gap	Nodes	PD gap
NoCuts	189.44 (423.68)	0.00 (0)	2170.66 (4054.09)	0.00 (0)	16945.58 (41242.04)	0.00 (0.000128)
Default	116.77 (420.09)	0.00 (0)	588.23 (1916.99)	0.00 (0)	16949.88 (41297.50)	0.00 (0.000128)
Random	95.70 (285.05)	0.00 (0)	1416.96 (3820.01)	0.00 (0)	21463.16 (59411.07)	0.00 (0.000361)
NV	199.70 (436.25)	0.00 (0)	1618.42 (3089.12)	0.00 (0)	20673.32 (62526.13)	0.00 (0.00022)
Eff	194.17 (439.35)	0.00 (0)	1575.88 (2742.66)	0.00 (0)	14909.93 (28575.12)	0.00 (0)
SBP	1.16 (2.04)	0.00 (0)	698.41 (2869.65)	0.00 (0)	13537.59 (22527.45)	0.00 (0)
HEM (Ours)	**1.11 (1.46)**	**0.00 (0)**	**311.64 (1309.94)**	**0.00 (0)**	**10463.85 (18491.25)**	**0.00 (0)**

	MIK		CORLAT		Load Balancing	
Method	Nodes	PD gap	Nodes	PD gap	Nodes	PD gap
NoCuts	395290.17 (120526.21)	0.09 (0.018)	97098.72 (119287.56)	2.000000e+18 (1.4E+19)	108.20 (56.28)	0.94 (0.12)
Default	224746.60 (179450.80)	0.02 (0.033)	70215.01 (113515.62)	2.666667e+18 (1.61E+19)	**65.22 (55.34)**	0.43 (0.073)
Random	403618.10 (115802.29)	0.07 (0.035)	74149.90 (109043.28)	2.000000e+18 (1.4E+19)	107.05 (68.05)	0.79 (0.133)
NV	397025.47 (106676.73)	0.08 (0.028)	77943.73 (111355.03)	4.666667e+18 (2.11E+19)	81.91 (38.55)	0.82 (0.11)
Eff	406832.83 (113363.27)	0.07 (0.033)	95956.53 (120858.92)	5.333333e+18 (2.25E+19)	86.22 (45.35)	0.82 (0.11)
SBP	417070.37 (133702.50)	0.07 (0.030)	62297.99 (109664.21)	6.666667e+17 (8.14E+18)	138.37 (53.79)	0.65 (0.06)
HEM(Ours)	**220547.93 (172537.94)**	**0.02 (0.028)**	**51929.71 (100973.74)**	**0.02 (0.051)**	74.47 (60.98)	**0.42 (0.072)**

	Anonymous		MIPLIB mixed neos		MIPLIB mixed supportcase	
Method	Nodes	PD gap	Nodes	PD gap	Nodes	PD gap
NoCuts	20110.58 (14167.51)	8.333333e+18 (2.76E+19)	169348.83 (117745.23)	2.500000e+19 (4.33E+19)	5971.00 (8679.98)	9.19 (19.29)
Default	20025.78 (13056.50)	8.333333e+18 (2.76E+19)	161366.25 (107049.96)	2.500000e+19 (4.33E+19)	**4055.04 (7404.61)**	11.73 (31.52)
Random	19824.48 (12366.55)	1.000000e+19 (3E+19)	**143930.17 (95296.41)**	2.500000e+19 (4.33E+19)	4656.13 (7745.46)	6.05 (14.69)
NV	**19313.33 (12391.94)**	8.333333e+18 (2.76E+19)	150046.50 (94801.62)	2.500000e+19 (4.33E+19)	4986.21 (9024.19)	2.78 (10.08)
Eff	19526.23 (12116.80)	6.666667e+18 (2.49E+19)	144128.83 (93404.76)	2.500000e+19 (4.33E+19)	4450.88 (7845.48)	5.58 (15.40)
SBP	19351.67 (12337.81)	6.666667e+18 (2.49E+19)	177736.25 (122005.81)	2.500000e+19 (4.33E+19)	5618.08 (9765.43)	0.14 (0.26)
HEM(Ours)	20191.28 (13219.21)	**1.666667e+18 (1.28E+19)**	177735.83 (129020.42)	**2.500000e+19 (4.33E+19)**	4844.88 (9996.16)	**0.14 (0.25)**

Although we can offline generate training samples as much as possible using a MILP solver, high sample efficiency is significant as generating samples can be extremely time-consuming in practice.

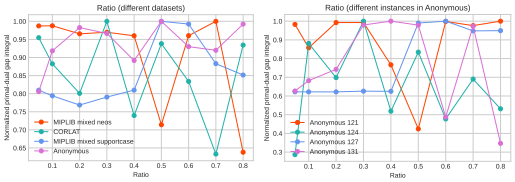
F Additional Results

F.1 More motivating results

Ratio matters. To evaluate the effect of the ratio of selected cuts on solving MILPs, we focus on the Normalized Violation (NV) cut selection method with different ratios of selected cuts. (1) We first evaluate the NV methods that select $5\%, 10\%, 20\%, 30\%, 40\%, 50\%, 60\%, 70\%$, and 80% of candidate cuts, respectively, on four datasets. The results in Fig. 4a show that the NV achieves better solver performance with larger ratios on CORLAT and MIPLIB mixed neos. The results demonstrate that the ratio that leads to better solver performance is variable over different datasets, which implies that learning dataset-dependent ratios is important. (2) We then evaluate the NV methods that select $5\%, 10\%, 20\%, 30\%, 40\%, 50\%, 60\%, 70\%$, and 80% of candidate cuts, respectively, on four instances from the Anonymous dataset. The results in Fig. 4b show that NV achieves better solver performance with larger ratios on Anonymous 121 and Anonymous 131. The results demonstrate that the ratio that leads to better solver performance is variable over different instances from the same dataset, which implies that learning instance-dependent ratios is significant as well.

F.2 More results of main evaluation

In this section, we provide additional results of the main evaluation. The results in Table 7 show the performance of HEM and baselines in terms of the total number of nodes and the primal-dual gap. On easy datasets, HEM and most baselines find the optimal solution within the time limit as the primal-dual gap converges to zero. In terms of the primal-dual gap, HEM outperforms all the



(a) NV with different ratios on four datasets. (b) NV with different ratios on Anonymous.

Figure 4: We use the Normalized Violation (NV) rule. The results in (c) show that NV with different given ratios achieve variable normalized PD integral on four datasets. The results in (d) show that NV with different ratios achieve variable normalized PD integral on different in-

Table 8: Comparsion between HEM, HEM without the higher-level model on more datasets.

	Set Covering				Multiple Knapsack			
Method	Time (s)	Nodes	PD gap	PD integral	Time (s)	Nodes	PD gap	PD integral
NoCuts	6.31 (4.61)	189.44 (423.68)	0.00 (0)	56.99 (38.89)	9.88 (22.24)	16945.58 (41242.04)	0.00 (0.000128)	16.41 (14.16)
Default	4.41 (5.12)	116.77 (420.08)	0.00 (0)	55.63 (42.21)	9.90 (22.24)	16949.87 (41297.49)	0.00 (0.000128)	16.46 (14.25)
SBP	1.91 (0.36)	1.16 (2.04)	0.00 (0)	38.96 (8.66)	7.74 (12.36)	13537.58 (22527.45)	0.00 (0)	16.45 (16.62)
HEM w/o H	**1.84 (0.31)**	1.18 (2.03)	0.00 (0)	**37.69 (8.33)**	7.36 (12.90)	12418.85 (23256.47)	0.00 (0)	14.01 (10.94)
HEM (Ours)	1.85 (0.31)	**1.09 (1.46)**	**0.00 (0)**	37.92 (8.46)	**6.13 (9.61)**	**10463.84 (18491.25)**	**0.00 (0)**	**13.63 (9.63)**

	MIK				Load Balancing			
Method	Time (s)	Nodes	PD gap	PD integral	Time (s)	Nodes	PD gap	PD integral
NoCuts	300.01 (0.009)	395290.16 (120526.21)	0.09 (0.018)	2355.87 (996.08)	300.00 (0.12)	108.20 (56.28)	0.94 (0.12)	14853.77 (951.42)
Default	179.62 (122.36)	224746.60 (179450.80)	0.02 (0.033)	844.40 (924.30)	300.00 (0.06)	**65.22 (55.34)**	0.43 (0.07)	9589.19 (1012.95)
SBP	286.07 (41.81)	417070.36 (133702.49)	0.07 (0.0295)	2053.30 (740.11)	300.00 (0.10)	138.37 (53.79)	0.65 (0.06)	12535.30 (741.43)
HEM w/o H	218.87 (115.97)	297058.97 (189410.43)	0.04 (0.039)	1321.63 (1165.23)	300.03 (0.04)	70.93 (60.36)	**0.42 (0.07)**	**9475.16 (1005.81)**
HEM (Ours)	**176.12 (125.18)**	**220547.93 (172537.94)**	**0.02 (0.028)**	**785.04 (790.38)**	**300.00 (0.04)**	74.47 (60.98)	**0.42 (0.07)**	**9496.42 (1018.35)**

	Anonymous				MIPLIB mixed supportcase			
Method	Time (s)	Nodes	PD gap	PD integral	Time (s)	Nodes	PD gap	PD integral
NoCuts	246.22 (94.90)	20110.58 (14167.51)	8.333333e+18 (2.76E+19)	18297.30 (9769.42)	170.00 (131.60)	5971.00 (8679.98)	9.19 (19.29)	9927.96 (11334.07)
Default	244.02 (97.72)	20025.78 (13056.50)	8.333333e+18 (2.76E+19)	17407.01 (9736.19)	164.61 (135.82)	4055.04 (7404.61)	11.73 (31.52)	9672.34 (10668.24)
SBP	245.71 (92.46)	**19351.66 (12337.81)**	6.666667e+18 (2.49E+19)	18188.63 (9651.85)	165.61 (135.25)	5618.08 (9765.43)	0.14 (0.26)	7408.65 (7903.47)
HEM w/o H	251.00 (88.45)	21192.40 (16436.32)	5.000000e+18 (2.18E+19)	17226.84 (9553.90)	**156.96 (133.35)**	**3779.83 (7465.75)**	0.56 (1.43)	7709.19 (8655.48)
HEM (Ours)	**241.68 (97.23)**	20191.28 (13219.21)	**1.666667e+18 (1.28E+19)**	**16077.15 (9108.21)**	162.96 (138.21)	4844.87 (9996.15)	**0.14 (0.25)**	**6874.80 (6729.97)**

baselines on medium and hard datasets, especially on CORLAT.

F.3 More results of ablation study

In this section, we provide addition results of ablation study.

F.3.1 Analysis of comparsion between HEM-ratio and SBP

A possible reason is that it is more difficult to train a sequence model than training a multi-layer perceptron and thus the sequence model may suffer from inefficient exploration and be trapped to the local optimum.

F.3.2 Contribution of each component

To understand the contribution of each component of HEM, we provide addition results of HEM and HEM without the higher-level model on Set Covering, Multiple Knapsack, MIK, Load Balancing, Anonymous, and MIPLIB mixed supportcase. The results in Table 8 show that HEM outperforms HEM w/o H in terms of the solving time, the primal-dual gap, and the primal-dual gap integral on several challenging datasets, demonstrating the importance of our proposed higher-level model. Moreover, HEM w/o H significantly outperforms SBP in terms of the solving time, the primal-dual gap, and the primal-dual gap integral on several challenging datasets, demonstrating the significance of our proposed lower-level model.

F.3.3 The importance of tackling **P1-P3** in cut selection

To understand the importance of tackling **P1-P3** in cut selection, we provide additional results of HEM, HEM-ratio, and HEM-ratio-order on Set Covering, Multiple Knapsack, MIK, Load Balancing, Anonymous, and MIPLIB mixed supportcase. Here we refresh what HEM, HEM-ratio, HEM-ratio-order mean. (1) **HEM**. HEM tackles **P1-P3** in cut selection simultaneously. (2) **HEM-ratio**. In order not to learn how many cuts should be selected, we remove the higher-level model of HEM and force the lower-level model to select a fixed ratio of cuts. We denote it by HEM-ratio. Note that HEM-ratio is different from HEM w/o H (see Appendix E). HEM-ratio tackles **P1** and **P3** in cut selection. (3) **HEM-ratio-order.** To further mute the effect of the order of selected cuts, we reorder the selected cuts given by HEM-ratio with the original index of the generated cuts, which we denote by HEM-ratio-order. HEM-ratio-order mainly tackles **P1**.

The results in Table 9 suggest the following. HEM-ratio-order outperforms Default and NoCuts on several datasets, demonstrating that tackling **P1** by data-driven methods is crucial. HEM signifi-

Table 9: Comparsion between HEM, HEM-ratio, and HEM-ratio-order on more datasets.

	Set Covering				Multiple Knapsack			
Method	Time (s)	Nodes	PD gap	PD integral	Time (s)	Nodes	PD gap	PD integral
NoCuts	6.31 (4.61)	189.44 (423.68)	0.00 (0)	56.99 (38.89)	9.88 (22.24)	16945.58 (41242.04)	0.00 (0.000128)	16.41 (14.16)
Default	4.41 (5.12)	116.77 (420.08)	0.00 (0)	55.63 (42.21)	9.90 (22.24)	16949.87 (41297.49)	0.00 (0.000128)	16.46 (14.25)
SBP	1.91 (0.36)	1.16 (2.04)	0.00 (0)	38.96 (8.66)	7.74 (12.36)	13537.58 (22527.45)	0.00 (0)	16.45 (16.62)
HEM-ratio-order	2.11 (0.38)	1.11 (1.29)	0.00 (0)	42.01 (9.88)	10.46 (29.74)	18434.20 (59254.10)	0.00 (0.000128)	16.92 (18.19)
HEM-ratio	2.10 (0.40)	1.11 (1.18)	0.00 (0)	41.95 (9.82)	7.63 (12.64)	13307.73 (24339.3)	0.00 (0)	16.19 (15.16)
HEM (Ours)	**1.85 (0.31)**	**1.09 (1.46)**	**0.00 (0)**	**37.92 (8.46)**	**6.13 (9.61)**	**10463.84 (18491.25)**	**0.00 (0)**	**13.63 (9.63)**

	MIK				Load Balancing			
Method	Time (s)	Nodes	PD gap	PD integral	Time (s)	Nodes	PD gap	PD integral
NoCuts	300.01 (0.009)	395290.16 (120526.21)	0.09 (0.018)	2355.87 (996.08)	300.00 (0.12)	108.20 (56.28)	0.94 (0.12)	14853.77 (951.42)
Default	179.62 (122.36)	224746.60 (179450.80)	0.02 (0.033)	844.40 (924.30)	300.00 (0.06)	**65.22 (55.34)**	0.43 (0.07)	9589.19 (1012.95)
SBP	286.07 (41.81)	417070.36 (133702.49)	0.07 (0.0295)	2053.30 (740.11)	300.00 (0.10)	138.37 (53.79)	0.65 (0.06)	12535.30 (741.43)
HEM-ratio-order	282.92 (42.07)	417397.10 (132077.3)	0.06 (0.034)	2072.69 (849.16)	300.11 (0.11)	145.18 (56.52)	0.65 (0.061)	12368.12 (726.77)
HEM-ratio	283.75 (39.87)	401540.97 (131295.8)	0.07 (0.034)	1869.66 (978.85)	300.10 (0.098)	148.92 (59.12)	0.65 (0.058)	12410.84 (715.44)
HEM (Ours)	**176.12 (125.18)**	**220547.93 (172537.94)**	**0.02 (0.028)**	**785.04 (790.38)**	**300.00 (0.04)**	74.47 (60.98)	**0.42 (0.07)**	**9496.42 (1018.35)**

	Anonymous				MIPLIB mixed supportcase			
Method	Time (s)	Nodes	PD gap	PD integral	Time (s)	Nodes	PD gap	PD integral
NoCuts	246.22 (94.90)	20110.58 (14167.51)	8.33e+18 (2.76E+19)	18297.30 (9769.42)	170.00 (131.60)	5971.00 (8679.98)	9.19 (19.29)	9927.96 (11334.07)
Default	244.02 (97.72)	20025.78 (13056.50)	8.33e+18 (2.76E+19)	17407.01 (9736.19)	164.61 (135.82)	**4055.04 (7404.61)**	11.73 (31.52)	9672.34 (10668.24)
SBP	245.71 (92.46)	**19351.66 (12337.81)**	6.67e+18 (2.49E+19)	18188.63 (9651.85)	165.61 (135.25)	5618.08 (9765.43)	0.14 (0.26)	7408.65 (7903.47)
HEM-ratio-order	245.45 (94.99)	20495.80 (12472.44)	5.00e+18 (2.18E+19)	16496.06 (9282.15)	169.45 (132.55)	6252.63 (9827.98)	4.25 (15.97)	9226.95 (9995.94)
HEM-ratio	245.17 (95.21)	20942.07 (13379.46)	5.00e+18 (2.18E+19)	16148.82 (9247.48)	163.03 (137.16)	5551.29 (10708.46)	7.54 (21.85)	9979.35 (11048.11)
HEM (Ours)	**241.68 (97.23)**	20191.28 (13219.21)	**1.67e+18 (1.28E+19)**	**16077.15 (9108.21)**	**162.96 (138.21)**	4844.87 (9996.15)	**0.14 (0.25)**	**6874.80 (6729.97)**

Table 10: Policy evaluation on MIPLIB mixed neos and MIPLIB mixed supportcase with a time limit *three hours*.

	MIPLIB mixed neos					MIPLIB mixed supportcase				
Method	Time (s)	Nodes	PD gap	PD integral	Improvement (PD integral, %)	Time (s)	Nodes	PD gap	PD integral	Improvement (PD integral, %)
NoCuts	8,126.15 (4631.32)	5,058,282.42 (5067358)	0.97 (1.14)	369,180.71 (368274)	NA	3,616.09 (4703.68)	258,543.71 (692821)	0.00 (0.0096)	37,858.65 (59578.6)	NA
Default	8,129.27 (4625.92)	4,800,372.67 (4815222)	0.94 (1.07)	392,324.09 (393266)	-6.27	3,997.69 (4720.2)	188,844.71 (599665)	0.01 (0.012)	56,375.64 (106694)	-48.91
Random	8,125.44 (4632.53)	5,107,627.25 (5114152)	0.95 (1.09)	395,694.74 (393445)	-7.18	2,605.78 (3993.84)	**8,458.96 (14785.9)**	0.01 (0.029)	44,222.39 (70937.6)	-16.81
NV	8,133.64 (4618.37)	4,930,498.92 (4930971)	0.91 (1.03)	326,315.04 (391163)	11.61	**2,561.10 (3980.44)**	34,851.08 (142069)	0.00 (0.0095)	27,908.00 (37742.2)	26.28
Eff	8,130.78 (4623.31)	4,788,568.75 (4804443)	0.94 (1.07)	395,640.44 (393572)	-7.17	3,105.98 (4308.57)	182,187.63 (543167)	0.01 (0.028)	39,932.37 (58307.3)	-5.48
SBP	8,130.63 (4626.62)	4,763,378.00 (4829037)	0.91 (1.03)	388,564.35 (398176.3)	-5.25	3,014.63 (4082.19)	146,180.96 (543662.45)	0.00 (0.0084)	24,447.37 (55984.9)	35.42
HEM(Ours)	**8,124.32 (4634.54)**	**4,748,599.50 (4816327)**	**0.78 (0.82)**	**194,557.87 (345035)**	**47.30**	3,465.48 (4485.11)	52,750.08 (140410)	**0.00 (0.0087)**	**17,885.98 (24045.9)**	**52.76**

cantly outperforms HEM-ratio in terms of the primal-dual gap integral, demonstrating the significance of tackling **P2**. HEM-ratio outperforms HEM-ratio-order on several datasets, which demonstrates the importance of tackling **P3**. Moreover, HEM-ratio performs better than SBP in terms of the solving time and the primal-dual gap integral on all six datasets except Set Covering and MIPLIB mixed supportcase, which shows the superiority of formulating the cut selection as a seuqence to sequence learning problem over formulating it as a scoring task. However, HEM-ratio and HEM-ratio-order perform a little worse than SBP on Set Covering and MIPLIB mixed supportcase. A possible reason is that it is more difficult to train a sequence model than training a multi-layer perceptron and thus the sequence model may suffer from inefficient exploration and be trapped to the local optimum. Please refer to Appendix F.3.1 for a detailed analysis.

F.4 More visualization results

In this part, we provide additional visualization results on Set Covering and MIK. On MIK, we visualize the cuts selected by HEM-ratio and SBP on a randomly sampled instance. We perform principal component analysis (Mohri et al., 2018) on selected cuts to reduce the cut features to two-dimensional space. Colored points illustrate reduced cut features. To visualize the diversity of selected cuts, we use dashed lines to connect the points with the smallest and largest x,y coordinates. The results in Figure 6 still show that HEM-ratio selects much more diverse cuts than SBP on MIK. However, HEM-ratio performs poorer than SBP on Set Covering (see Appendix F.3.1 for a detailed analysis). Therefore, we visualize the cuts selected by HEM and SBP on a randomly sampled instance from Set Covering. Although HEM learns the number of cuts that should be selected, we find that HEM selects much fewer number of cuts than SBP. Specifically, HEM selects 25 cuts, while SBP selects 158 cuts. Interestingly, the results in Figure 6

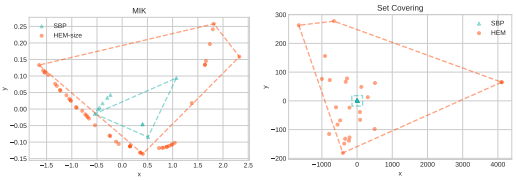


Figure 6: We perform principal component analysis on cuts selected by HEM-ratio/HEM and SBP. Each colored point illustrates a reduced cut feature. To visualize the diversity of selected cuts, we use dashed lines to connect the points with the smallest and largest x,y coordinates.

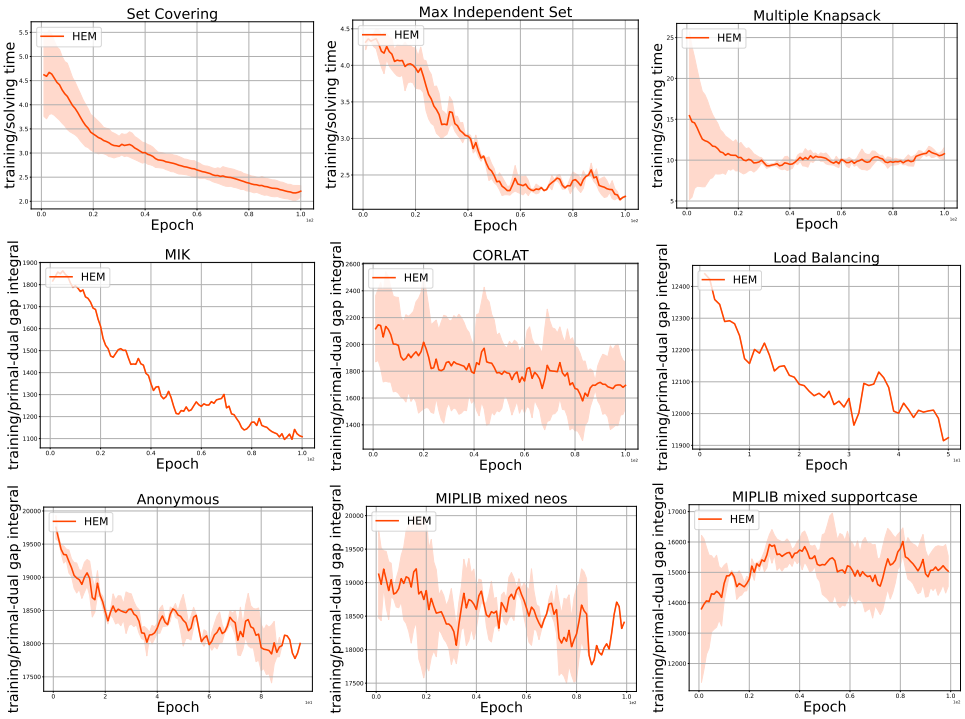


Figure 5: Training curves of HEM on all nine datasets. The x-axis corresponds to the training epochs. The y-axis corresponds to the average solving time on easy datasets and the primal-dual gap integral on the other datasets. The solid curves correspond to the mean and the shaded region to the standard deviation over three random seeds. For visual clarity, we smooth curves.

show that SBP selects 158 similar cuts with high
scores, while HEM selects much more diverse cuts than SBP.

F.5 Evaluation with a time limit of three hours

In this section, we aim to evaluate whether HEM can generalize well to solving problems within a much longer time limit, which is also common in real-world applications. Specifically, we evaluate HEM on two extremely challenging MIPLIB datasets within a time limit of *three hours*. The results in Table 10 show that HEM significantly outperforms all the baselines, especially in terms of the primal-dual gap integral on MIPLIB mixed neos and MIPLIB mixed supportcase. In terms of the primal-dual gap, HEM also outperforms the baselines. Moreover, HEM performs a little better than baselines in terms of the solving time on MIPLIB mixed neos, but HEM performs poor in terms of the solving time on MIPLIB mixed supportcase. It is interesting that the primal-dual gap integral is not always consistent with the solving time. To improve the performance of HEM in terms of the solving time, we can set the reward as the solving time instead of the primal-dual gap integral.

F.6 Training curves

In this section, we provide the training curves of HEM on all nine datasets. The results in Fig. 5 show that the performance of our learned policies in terms of the solving time or the primal-dual gap integral drops with the epochs, demonstrating the effectiveness of our learning process.