THE MAXIMUM HAMILTONIAN PATH PROBLEM
WITH SPECIFIED ENDPOINT(S)

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Le problème de la chaîne Hamiltonienne de poids maximum avec extrémité(s) prédéterminée(s)

Résumé

Cet article traite des différents problèmes de la chaîne Hamiltonienne, nommés $HPP_{s,t}$ lorsque les deux extrémités sont connues à l'avance et $HPP_s$ lorsqu'une seule est prédéterminée. Nous montrons que $HPP_{s,t}$ est 1/2-différentielle approximable et n'est pas approximable à mieux de 649/650. Ensuite, nous prouvons que la version $HPP_s$ est mieux approximable avec un ratio de 2/3. Basés sur ces résultats, nous obtenons des bornes pour la mesure standard: une 1/2-approximation standard pour $HPP_{s,t}$, et une 2/3-approximation standard pour $HPP_s$. Nous améliorons ce ratio à 2/3 pour $\text{Max } HPP_{s,t}[a,2a]$ (lorsque les arêtes ont un coût appartenant à l'intervalle $[a,2a]$), à 5/6 pour $\text{Max } HPP_s[a,2a]$ et à finalement 3/4 pour $\text{Min } HPP_{s,t}[a,2a]$, à 3/4 pour $\text{Min } HPP_s[a,2a]$.

Mots-clés: Algorithmes approchés; Mesure différentielle; Mesure standard; Réductions

The maximum Hamiltonian Path Problem with specified endpoint(s)

Abstract

This paper deals with the problem of constructing Hamiltonian paths of optimal weight, called $HPP_{s,t}$ if the two endpoints are specified, $HPP_s$ if only one endpoint is specified. We first show that $HPP_{s,t}$ is 1/2- differential approximable and cannot be differential approximable greater than 649/650. We next demonstrate that, when dealing with one specified endpoint, we improve to 2/3 the ratio. Based upon these results, we obtain new bounds for standard ratios: a 1/2-standard approximation for $\text{Max } HPP_{s,t}$ and a 2/3 for $\text{Max } HPP_s$, which can be improved to 2/3 for $\text{Max } HPP_{s,t}[a,2a]$ (all the edge weights are within an interval $[a,2a]$), to 5/6 for $\text{Max } HPP_s[a,2a]$ and to 2/3 for $\text{Min } HPP_{s,t}[a,2a]$, to 3/4 for $\text{Min } HPP_s[a,2a]$.

Keywords: Approximate algorithms; Differential ratio; Performance ratio; Analysis of Algorithms;
1 Introduction

Routing design problems are of a major importance in combinatorial optimization, and the most important ideas of algorithmic have been applied to them during the last twenty years, see Christofides [4], Fisher et al [12], Hassin and Rubinstein [15] and Engebretsen [11]. We will be concerned with some problems closely related to the Maximum Traveling Salesman problem, namely, the problem of finding a Hamiltonian path of maximum weight. We will study two variants depending on the number of specified endpoints (one or two) of the path. Max HPP$_s$ and Max HPP$_{s,t}$ respectively denote the Hamiltonian path problem with one fixed endpoint $s \in V$ and two fixed endpoints $s, t \in V$. To our knowledge, these two latter problems have not been studied before, whereas their minimization versions have been studied by Hoogeveen [17] and Guttmann-beck et al. [14] (in particular, it is well known that the minimization problems are NP-hard).

We also deal with a variant called HPP$_{s,t}[a,b]$, where the edge-weights are in the set $\{a, a+1, \ldots, b-1, b\}$. Both Min- and Max HPP$_{s,t}$ are NP-hard, even in their restricted versions with $b > a$, since they are polynomial-time Karp-reducible [19] to each other.

We focus on the design of approximation algorithms with guaranteed performance ratios, that run within polynomial time and produce sub-optimal solutions. Usually, the scientific community works on the ratio (called standard ratio) of the cost of the solution generated by the algorithm to the optimal cost, in the worst-case. However, we mainly refer in this article to another ratio called differential ratio which measures the worst ratio of, on the one hand, the difference between the cost of the solution generated by the algorithm and the worst cost, and on the other hand, the difference between the optimal cost and the worst cost. This measure, studied by Ausiello et al. [3], Fisher et al. [12] and more recently by Demange and Paschos [10], leads to new algorithms taking into account the extreme solutions of the instance, and provides the opportunity to better understand these problems. There are great differences between standard and differential approximation for the Hamiltonian path problems. For instance, we can easily prove that the Best Neighbor Heuristic [12] is 1/3-standard approximable for Max HPP$_s$ or that we have a trivial standard approximation scheme for Max HPP$_{s,t}[n; n+5]$; however, for the differential ratio, the Best Neighbor Heuristic is not approximable with any constant ratio for Max HPP$_s$ and Max HPP$_{s,t}[n; n+5]$ is not approximable with ratio greater than 649/650. We present along this paper many examples to illustrate the difference between these two measures.

We now give some standard definitions in the field of optimization and approximation theory. For a more detailed statement of this theory, we refer the reader to Ausiello et al. [2], [1], Hochbaum [16].

**Definition 1.1** An NP-optimization problem $\pi \in NPO$ is a five-tuple $(D, sol, m, Triv, goal)$ such that:

(i) $D$ is the set of instances and is recognizable in polynomial-time.

(ii) Given an instance $I \in D$, $sol[I]$ is the set of feasible solutions of $I$; moreover, there exists a polynomial $P$ such that, for any $x \in sol[I]$, $|x| \leq P(|I|)$; furthermore, it is decidable in polynomial time whether $x \in sol[I]$ for any $I$ and for any $x$ such that $|x| \leq P(|I|)$. Finally, there is a feasible solution $Triv(I)$\footnote{The common definition of class $NPO$ does not require the existence of a trivial solution.} computable in polynomial-time for any $I$.

(iii) Given an instance $I$ and a solution $x$ of $I$, $m[I,x]$ denotes the positive integer value of $x$. The function $m$ is computable in polynomial time and is also called the objective function.

(iv) $goal \in \{Max, Min\}$. 

\[\diamond\]
We call $\bar{\text{goal}}^2$ the complementary notion of goal and $\pi$ the NPO-problem $(D, \text{sol}, m, \text{Triu}, \bar{\text{goal}})$. The goal of an NPO-optimization problem with respect to an instance $I$ is to find an optimum solution $x^*$ such that $OPT(I) = m[I, x^*] = \text{goal}(m[I, x] : x \in \text{sol}(I))$. Another important solution of $\pi$ is a worst solution $x_\ast$ defined by: $WOR(I) = m[I, x_\ast] = \text{goal}(m[I, x] : x \in \text{sol}(I))$. A worst solution for $\pi$ is an optimal solution for $\pi$ and vice versa. In Ausiello et al. [3], the term trivial solution referred to as worst solution and all the exposed examples have the property that a worst solution can be trivially computed in polynomial-time. For example, this is the case of the maximum Cut problem where, given a graph, the worst solution is the empty edge-set, or the Bin-Packing problem where we can trivially put the items using a distinct bin per item. On the contrary, since a worst solution of the maximum weight Hamiltonian path from $s$ to $t$ is an optimal solution of its corresponding minimization version, the computation of such a solution is far from being trivial! The same property occurs for the $f$-depth Spanning Tree problem [22] or all the problems exposed in [20].

Approximate algorithms and reductions. In order to study algorithms performances, there are two known measures: standard ratio [13], [2], [6] and differential ratio [10], [3] and [5].

Definition 1.2 Let $\pi$ be an NPO problem and $x$ be a feasible solution of an instance $I$. We define the performance ratio of $x$ with respect to $\pi$ as instance $I$ as

\begin{itemize}
  \item (standard ratio) $\rho[\pi](I, x) = \min \{ \frac{m[I, x]}{OPT(I)} \}$
  \item (differential ratio) $\delta[\pi](I, x) = \frac{WOR(I) - m[I, x]}{WOR(I) - OPT(I)}$
\end{itemize}

The performance ratio is a number less than or equal to 1, and is equal to 1 if and only if $m[I, x] = OPT(I)$. Remark that, compared to some definitions, we have inverted the standard performance ratio in the case of minimization problems so that the ratio value is always between 0 and 1. Let $\pi$ be an NPO problem. For any instance $I$ of $\pi$, a polynomial time algorithm $A$ returns a feasible solution $x^A$. The performance of $A$ with respect to $\pi$ on the instance $I$ is the quantity $RA[\pi](I) = R[\pi](I, x^A)$. We say that $A$ is an $r$-approximation algorithm with respect to $\pi$ if for any instance $I$, we have $RA[\pi](I) \geq r$.

Definition 1.3 For any performance ratio $R \in \{\delta, \rho\}$,

\begin{itemize}
  \item an NPO problem belongs to the class APX(R) if there exists an $r$-approximation with respect to $R$ for some constant $r \in [0,1]$.\footnote{If goal = Max, then goal = Min and goal = Max.}
  \item an NPO problem belongs to the class PTAS(R) if there exists an $r$-approximation $A_r$ for any constant $r \in [0,1]$. The family $\{A_r\}_0<r<1$ is said to be an approximation scheme.
\end{itemize}

Clearly, the following inclusion holds for any measure $R \in \{\delta, \rho\}$: PTAS(R) $\subseteq$ APX(R). As it is usually done, we will denote by APX and PTAS, respectively, the classes APX($\rho$) and PTAS($\rho$). We could argue whether the differential ratio is really pertinent: the authors of [10] and [8] answered positively to that question and concluded that this measure is complementary with the standard ratio. As shown in [8], many problems can have different behavior patterns depending on whether the differential or standard ratio is chosen: consider for instance Vertex Covering or Dominating Set problems. On the other hand, there are problems that establish some connections between the differential and the standard ratio, like Bin Packing [9] or maximum weight bounded-depth spanning tree [22]. Besides, we show that there are,
tight links between both measures for the problems dealt with in the case where the edge-weights have lower and upper bounds.

Now, consider the following approximation preserving reductions between pairs \((\pi, R)\).

**Definition 1.4** For \(\pi_i \in NPO\) and \(R_i \in \{\delta, \rho\}, i = 1, 2,\)

- an \(A\)-reduction from \((\pi_1, R_1)\) to \((\pi_2, R_2)\), denoted by \((\pi_1, R_1) \leq_A (\pi_2, R_2)\),

is a triplet \((\alpha, f, c)\) such that:

(i) \(\alpha: D_{\pi_1} \mapsto D_{\pi_2}\), transforms an instance of \(\pi_1\) into an instance of \(\pi_2\) in polynomial-time.

(ii) \(f: sol_{\pi_2}[\alpha(I)] \mapsto sol_{\pi_1}[f(I)]\), transforms solutions for \(\pi_2\) into solutions for \(\pi_1\) in polynomial-time.

(iii) \(c: [0; 1] \mapsto [0; 1]\) (called expansion of the \(A\)-reduction) is a function verifying \(c^{-1}(0) \subseteq \{0\}\) and \(\forall \varepsilon \in [0; 1], \forall I \in D_{\pi_1}, \forall x \in sol_{\pi_2}[\alpha(I)]: R_2[\pi_2](\alpha(I), x) \geq c(\varepsilon) \rightarrow R_1[\pi_1](I, f(x)) \geq c(\varepsilon)\).

- an \(A \ast P\)-reduction from the pair \((\pi_1, R_1)\), to the pair \((\pi_2, R_2)\), denoted by \((\pi_1, R_1) \leq_{A \ast P} (\pi_2, R_2)\),

is an \(A\)-reduction from \((\pi_1, R_1)\) to \((\pi_2, R_2)\) such that the restriction of function \(c\) to some interval \([a; b]\) is bijective and \(c(1) = 1\) (note that \(c(\varepsilon)\) does not necessarily verify \(c^{-1}(0) \subseteq \{0\}\)). If \((\pi_1, R_1) \leq_{A \ast P} (\pi_2, R_2)\) with \(c(\varepsilon) = \varepsilon\) for \(i = 1\) and \(i = 2\), we say that \((\pi_1, R_1)\) is equivalent to \((\pi_2, R_2)\).

An \(A\)-reduction preserves constant approximation while \(A \ast P\)-reduction preserves approximation schemes. They are a natural generalization of those described by Dyer and Frieze [22] and Conforti et al. [4].

For a maximization problem, the usual ratio measures how the value of an approximate solution is placed in the interval between 0 and \(OPT(I)\). Hence, for a maximization problem, we have an \(A \ast P\)-reduction from the usual ratio to the differential ratio since \(WOR(I) \geq 0\):

**Lemma 1.5** If \(\pi = (D, sol, m, Triv, Max) \in NPO\), then \((\pi, \rho) \leq_{A \ast P} (\pi, \delta)\) with \(c(\varepsilon) = \varepsilon\).

Remark that, in general, there is a evident transfer of positive/negative result from one framework to the other.

## 2 The Hamiltonian path problem

The Hamiltonian path problem, also called the Traveling Salesman Path problem, is formally defined as follows.

**Definition 2.1** Consider a complete graph \(K_n\) with non-negative costs \(d(x, y)\) for each vertices pairs of \(K_n\). We want to find an optimal-cost Hamiltonian path, where the cost of a path is the sum of the weights on its edges. We refer this problem as \(HPP\). When one endpoint \(s\) (resp. two endpoints \(s\) and \(t\)) of Hamiltonian path are specified, we use the notation \(HPP_s\) (resp. \(HPP_{s,t}\))

If \(goal = Max\), the problem is called \(Max\ HPP\), else \(Min\ HPP\). We use the notation \(HPP, HPP_s\) or \(HPP_{s,t}\) when we consider without distinction the cases \(goal = Max\) or \(goal = Min\).

For the Hamiltonian Path problem with non specified endpoints, a lot of standard ratio approximation results can be derived for TSP (with \(goal = Min\) and \(goal = Max\)) thanks to a structural property of solutions and a trivial reduction to the Traveling Salesman problem: the first negative approximation
result (that we can deduce from [26]) states that it is not possible to approximate Min HPP within 1/\(f(|I|)\) where \(f\) is any integer function computable within polynomial time unless \(P = NP\). On the other hand, Min metric\(^3\) HPP is approximable within 2/3 [4] and Min HPP[1,2] is APX-complete (deduce from Papadimitriou and Yannakakis [24]). For Max HPP, the results are more optimistic since this problem is in APX. The best-known standard ratio is equal to 3/4 and can be deduced from [27].

The Hamiltonian Path problems with specified endpoints (resp. metric HPP\(_s\) or metric HPP\(_s,t\)) are as hard to approximate as HPP (resp. metric HPP). The question put by Johnson and Papadimitriou [18] on the relative hardness of the specified endpoint version compared to the non-specified is open. These conjectures are strengthened by the positive results given on these problems since the best-known standard ratios are respectively 2/3 and 3/5 for Min HPP\(_s\) [17] and Min HPP\(_s,t\) [17], [14]. Moreover, if we consider the case \(a \leq d(e) \leq 2a\) there are no specific results. For example Christofides' modification algorithm [17] remain a 2/3-standard ratio for Min HPP\(_s\)[a;2a]. To our knowledge, no standard approximation result has been found for Max HPP\(_s\) and Max HPP\(_s,t\).

We show that HPP\(_s\) is 2/3-approximable and HPP\(_s,t\) is 1/2-approximable under the differential framework. We can deduce from lemma (1.5) a 2/3-standard approximation for Max HPP\(_s\) and a 1/2-standard approximation for Max HPP\(_s,t\). Moreover, our technique allows to handle the case where all the edge weights are within an interval \(\rho\), for arbitrary \(\rho\), and more generally the case \(WOR(I) \geq \frac{1}{2}OPT(I)\).

Since we give a 3/4 (resp. 2/3)-standard approximation for Min HPP\(_s\)[a,2a] (resp. Min HPP\(_s,t\)[a,2a]), we improve the best-known bounds of 2/3 (resp. 3/5) for minimization versions given by Hoogeveen [17] (resp. Guttmann-beck et al. [14] or [17]).

## 3 Elementary properties

We present some relations between HPP, HPP\(_s\), HPP\(_s,t\) and different subcases. We prove that HPP\(_s,t\) is the most general problem. As a second step, we establish for each problem some connected relations between differential and standard ratios. In the following paragraph, without specification, the properties that we present for HPP\(_s,t\) are also true for HPP\(_s\) and HPP.

HPP\(_s,t\) is as hard as HPP\(_s\) (which is itself as hard as HPP) to approximate for both performance ratios. Moreover, from a differential approximability point of view, these different versions are very closed to the Traveling Salesman problem, even if we consider the restriction \(a \leq d(e) \leq b\).

**Lemma 3.1** for any goal \(g \in \{ \text{Min}, \text{Max} \}\), we have:

(i) (goal) TSP, \(\delta\) \(\leq^{A+P}\) (goal HPP\(_s,t\), \(\delta\)) with \(c(e) = \varepsilon\).

(ii) (goal) HPP, \(\delta\) \(\leq^{A+P}\) (goal TSP, \(\delta\)) with \(c(e) = \varepsilon\).

**Proof:** We only show the case goal = Max. Let \(I = (K, d)\) be an instance.

- For (i): Choose a vertex \(s\) in \(K\) and define \(I_v = (K, s, v, d)\) for all \(v \in V \setminus \{s\}\). If \(\mu_v\) is a Hamiltonian path from \(s\) to \(v\) of \(I_v\), we construct the Hamiltonian cycle \(\Gamma_v = \mu_v \cup \{(s,v)\}\). Then, we take \(\Gamma = \text{argmax}(m[I, \Gamma_v] : v \in V \setminus \{s\})\). Now, consider \(v^*\) such that \(OPT(I_{v^*}) + d(s, v^*) = OPT(I)\);

- For (ii): Transform \(I\) into instance \(\alpha(I) = (K_{n+1}, d')\) as follow: add a new vertex \(s\) to graph \(K_n\) and define \(d'(s,v) = a, \forall v, d'(e) = d(e)\) for other edges. Then, the proof is similar.

\(^3\)Verifying for all vertices \(x, y, z\) the inequality: \(d(x, y) \leq d(x, z) + d(z, y)\).
Note that the proof of item (ii) also holds for the standard ratio with \( d'(s, v) = 0 \) and we can deduce from [21] and item (ii) of lemma (3.1) that HPP is 2/3-differential approximable and HPP[1, 2] is 3/4-differential approximable. HPP[1,2] is \( NP \)-hard if and only if so is HPP[1,2], hence, computing a worst solution of HPP[1,2] is as hard as computing an optimal one. For \( goal = Min \), we also have the well-known result stemming from Sahni and Gonzalez [26] which affirms that if \( Min \ HPP_{s,t} \in APX \), then the following decision problem is polynomial: given a simple graph \( G = (V, E) \), does \( E' \subseteq E \) exists such that \( E' \) is a Hamiltonian path from \( s \) to \( t \) of \( G \)? Thus, we deduce that \( Min \ HPP_{s,t} \) is not in \( APX \) unless \( P = NP \), because the associated decision problem is \( NP \)-Complete.

Yet, the asymmetry in the approximability of both versions (\( Max \ HPP_{s,t} \) is in \( APX \) as later proved) can be considered as somewhat strange given the structural symmetry existing between them. Since differential approximation is stable under an affine transformation of the objective function, \( Max \ HPP_{s,t} \) and \( Min \ HPP_{s,t} \) are differential-equivalent \(^4\). Besides, another difference with the standard ratio is that \( Min \ HPP_{s,t} \) is not more difficult than the same problem with triangular inequality (called metric).

**Proposition 3.2** The following assertions hold:

(i) \( Min \ HPP_{s,t} \) is differential-equivalent to \( Max \ HPP_{s,t} \).

(ii) \( Min \ HPP_{s,t}[a,b] \) is differential-equivalent to \( Max \ HPP_{s,t}[a,b] \).

(iii) \( HPP_{s,t} \) is differential-equivalent to metric \( HPP_{s,t} \).

**Proof**: Let \( I = (K_n, s, t, d) \) be an instance, set \( d_{max} = \max_{e\in E} d(e) \) and \( d_{min} = \min_{e\in E} d(e) \).

- For (i) and (ii): \( (Min \ HPP_{s,t}, \delta) \preceq_{\text{Ap}} (Max \ HPP_{s,t}, \delta) \) with \( c(\varepsilon) = \varepsilon \).
  - We transform \( I \) into instance \( I' = (K_n, s, t, d') \) defined by: \( \forall e \in E, d'(e) = d_{max} + d_{min} - d(e) \).
  - For any Hamiltonian path \( \mu \) from \( s \) to \( t \), we have: \( m[I', \mu] = (|V| - 1)(d_{max} + d_{min}) - m[I, \mu] \).
  - Hence if \( m[I, \mu] \geq \varepsilon \text{OPT}(\varepsilon (I)) + (1-\varepsilon)\text{WOR}(\varepsilon (I)) \), then \( m[I, \mu] \leq \varepsilon \text{OPT}(I) + (1-\varepsilon)\text{WOR}(I) \).
  - Conversely, the proof is similar since \( \varepsilon \leq \varepsilon = 1d \).

- For (iii), the proof is similar, except that function \( d' \) is now defined by \( d'(e) = d_{max} + d(e) \).

The following easy theorem holds, thus giving a bridge between differential and standard ratios for \( goal = Max \) and \( goal = Min \), in the case where edge weights belong to an interval \([a, b]\).

**Theorem 3.3** (\( goal \ HPP_{s,t}[a,b], \rho) \preceq_{\text{Ap}} (goal \ HPP_{s,t}[a,b], \delta \) with the expansion verifying:

- \( c_1(\varepsilon) = \frac{(b-a)\varepsilon}{b} + \frac{a}{b} \) if \( goal = Max \)
- \( c_2(\varepsilon) = \frac{a}{b - (b-a)\varepsilon} \) if \( goal = Min \)

**Proof**: We only prove the \( goal = Max \) case. Let \( I \) be an instance and \( \mu \) be a Hamiltonian path from \( s \) to \( t \).

- If \( m[I, \mu] \geq \varepsilon \text{OPT}(I) + (1-\varepsilon)\text{WOR}(I) \), then \( m[I, \mu] \geq c_1(\varepsilon)\text{OPT}(I) \) since \( \text{WOR}(I) \geq \frac{3}{2} \text{OPT}(I) \).

\( HPP_{s,t}[a,b] \) (for \( a \) and \( b \) not depending on the instance) is "easy" to approximate with standard framework (i.e., \( HPP_{s,t}[a,b] \in APX \)), since even a worst solution is an \( a/b \)-approximation (take \( \varepsilon = 0 \) in theorem (3.3)), while this is not true with the differential measure. Nevertheless, we can deduce from

\(^4\)see definition (1.4)
this theorem that the hardness thresholds for standard and differential framework are identical since
Min \( HPP_{s,t}[a,b] \) is APX - complete.

**Corollary 3.4** For all \( b > a \geq 0 \), \( HPP_{s,t}[a,b] \notin PTAS(\delta) \) unless \( P = NP \).

For some values of \( a \) and \( b \), we can also establish a limit on its differential approximation. Keep in
mind the negative result of [11]: for any \( \epsilon > 0 \), no polynomial time algorithm can guarantee a standard
approximation ratio greater than, or equal to, \( \frac{11}{10} + \epsilon \) for TSP[1,6]. So, using item(i) of lemma(3.1) and
lemma(1.5), we deduce:

**Proposition 3.5** For all \( a \geq 0 \), \( HPP_{s,t}[a,a+5] \) is not approximable with differential ratio greater than
\( \frac{11}{10} \) unless \( P = NP \).

Note that this proposition does not hold for \( HPP_s \) and \( HPP_t \).

### 4 Approximate algorithms for these problems

In this section, we propose two types of algorithms which yield constant ratio. For \( Max \ HPP_s \), the
algorithm is obtained by getting several feasible solutions and by choosing the best one among them.
Each of these individual solutions has a differential approximation ratio tending towards zero with the
size of the instance. For \( Max \ HPP_{s,t} \), the algorithm is very different and takes into account the extreme
solutions. So, on the one hand, the algorithm tries to be the nearest from the best solution value and on
the other hand, tries to be the furthest from the worst solution value. In order to do that, it iteratively
provides a solution of value greater than \( (WOR(I_j) + OPT(I_j))/2 \), where \( I_j \) is the sub-graph built at step
\( j \).

#### 4.1 The algorithm for two specified endpoints version

\( Max \ HPP_{s,t} \) can also be regarded as the problem of determining a Hamiltonian cycle that contains edge
\((s,t)\). The algorithm works by finding a maximum weight 2-matching among 2-matchings containing
\((s,t)\) and at each step, merge two by two the cycles... The main idea consists in pointing out that the
above could have lost much more by merging in a different way the two cycles at each iteration. Thus, we will
build dynamically a bad solution that will actually depend on the choices made by the algorithm at each
iteration. Consider two cycles \( \Gamma_1 \) and two edges \((x_1,x_2) \in \Gamma_1 \) and \((y_1,y_2) \in \Gamma_2 \), we call \( localchange_i \) for
\( i = 1,2 \) the following process:

\[
localchange_i([\Gamma_1,(x_1,x_2)],(\Gamma_2,(y_1,y_2))) = \{(x_1,y_{3-i}),(x_2,y_i)\} \cup (\Gamma_1 \cup \Gamma_2 \setminus \{(x_1,x_2),(y_1,y_2)\})
\]

These two processes merge the cycles \( \Gamma_1 \) and \( \Gamma_2 \) into a unique cycle. Remark that the vertices order
is important in the processes; thus, edges \((x_1,x_2)\) or \((y_1,y_2)\) are implicitly given as directed edges and
we have: \( localchange_1([\Gamma_1,(x_1,x_2)],(\Gamma_2,(y_1,y_2))) = localchange_2([\Gamma_1,(x_1,x_2)],(\Gamma_2,(y_1,y_2))] \).
Moreover, when \( \Gamma_1 = \Gamma_2 \) and \((x_1,x_2)\) is not adjacent to \((y_1,y_2)\), these processes amount to simply local edges swaps.
We associate to \( localchange_i \) a function \( cost_i \) that represents the loss in merging two cycles.

\[
\text{cost}_i([(x_1,x_2),(y_1,y_2)]) = d(x_1,x_2) + d(y_1,y_2) - d(x_1,y_{3-i}) - d(x_2,y_i)
\]

([LocalchangeHPP_{s,t}]

input: An instance \((K_n,s,t,d)\);
output: A Hamiltonian path SOL from s to t of G;
Change the cost of (s, t) into |V|d_{max} + 1. Call d′ this function;
Compute a maximum weight 2-matching M = {Γi, i = 1, ..., k} of (K_n, d′);
Suppose that (s, t) ∈ Γ_1
Choose 2 consecutive edges (x_1^1, x_2^1) and (x_2^1, x_3^1) in Γ_1 different from (s, t);
sol_1 = Γ_1, e_1^1 = (x_1^1, x_2^1) and e_2^1 = (x_2^1, x_3^1);
For i=2 to k do

Choose 2 consecutive edges (x_1^i, x_2^i) and (x_2^i, x_3^i) in Γ_i;
If cost_i(e_1^{i-1}, (x_1^i, x_2^i)) ≤ cost_2(e_2^{i-1}, (x_2^i, x_3^i)) then
sol_i = localchange_i([sol_{i-1}, e_1^{i-1}], (Γ_i, (x_1^i, x_2^i)));
Suppose e_1^{i-1} = (x, y), and x_0^i is the other neighbor of x_1^i in Γ_i
Set e_1^i = (y, x_1^i) and e_2^i = (x_1^i, x_0^i);
Else
sol_i = localchange_i([sol_{i-1}, e_2^{i-1}], (Γ_i, (x_2^i, x_3^i)));
Suppose e_2^{i-1} = (x, y), and x_0^i is the other neighbor of x_2^i in Γ_i
Set e_1^i = (y, x_2^i) and e_2^i = (x_2^i, x_0^i);
End if;
End for i;
SOL = sol_k \ { (s, t) };

As this algorithm is polynomial, let us then show that SOL is an Hamiltonian path. First, remark that by construction, (s, t) belongs to every maximum weight 2-matching of (K_n, d′). Moreover, e_1^1 and e_2^1 obviously belong to sol_i for every iteration i ≤ k of the algorithm. These two facts lead to the result.

Theorem 4.1 The algorithm [LocalchangeHPP_{s,t}] is a \frac{1}{2}-differential approximation for Max HPP_{s,t} and this ratio is tight.

Proof: Given I = (K_n, s, t, d), an instance of Max HPP_{s,t}, we denote (i_2, ..., i_k) with i_j ∈ {1, 2} the sequence of choices produced by the algorithm such that, for j ∈ {2, ..., k}:

sol_j = localchange_{i_j}([sol_{j-1}, e_1^{j-1}], (Γ_j, (x_1^j, x_2^{j+1})))

Thus, d(sol_j) = d(sol_{j-1}) + d(Γ_j) - cost_{i_j}(j) with cost_{i_j}(j) = cost_1(e_1^{j-1}, (x_1^j, x_2^{j+1})). Summing up these equalities for j = 2 to k, and since d(sol_1) = d(Γ_1) and d(SOL) = d(sol_k) - d(s, t), we obtain:

\[ d(SOL) = d(M) - d(s, t) - \sum_{j=2}^{k} cost_{i_j}(j) \quad (4.1) \]

The main idea is to note that edge-subset \{e_{3-j}^1, (x_{3-j}^1, x_{4-j}^1) : j = 2, ..., k\} belongs to solution sol_k. Hence, we can "damage" the current solution by [local edges-swap from this edge subset]. More formally, consider solutions sol_j defined by sol_1 = sol_k and for j = 2, ..., k,

sol_j = localchange_{3-j}([sol_{j-1}, e_{3-j}^1], (sol_{j-1}, (x_{3-j}^1, x_{4-j}^1)))

Finally, proceeding as previously, we obtain d(sol_j) = d(M) - \sum_{j=2}^{k} cost_{i_j}(j) + cost_{3-j}(j). By construction, cost_{i_j}(j) + cost_{3-j}(j) ≥ 2cost_{i_j}(j) and WOR(I) ≤ d(sol_k') - d(s, t). Hence:

\[ WOR(I) ≤ d(M) - d(s, t) - 2\sum_{j=2}^{k} cost_{i_j}(j) \quad (4.2) \]
Remark that $M$ is an optimal weight 2-matching among the 2-matching of $(G, d)$ containing the edge $(s, t); \text{ thus,}$

$$OPT(I) \leq d(M) - d(s, t)$$

(4.3)

By combining expressions (4.3), (4.2) and (4.1), we obtain:

$$d(SOL) \geq \frac{1}{2} OPT(I) + \frac{1}{2} WOR(I)$$

We now show that this ratio is tight. Let $J_n = (K_n, s, t, d)$ be an instance defined by: $V = \{x_i, 1 \leq i \leq 2n, 2 \leq j \leq 2n + 1\} \cup \{(s, u, t)\}$, $d(x_i, x_i^{j+1}) = d(x_i^{j}, x_i^{j+1}) = 1 \forall j = 2, \ldots, 2n, d(x_i^{j}, x_i^{j+3}) = 1 \forall j = 2, \ldots, 2n - 1, d_n(s, x_i^{j}) = d_n(u, x_i^{j}) = d(u, x_i^{j}) = d(t, x_i^{j}) = 1$ and let the cost of all other edges be two. The 2-matching is composed of $\Gamma_1 = \{(s, u, t)\}$ and $\Gamma_j = \{x_i^{j}, x_i^{j+1}\} j = 2, \ldots, 2n + 1$. The edges produced by the algorithm are: $e_1 = (s, u), e_2 = (u, t), e_3 = (s, x_1^{j}), e_4 = (x_1^{j}, x_2^{j}), e_5 = (x_1^{j-1}, x_1^{j}), e_6 = (x_1^{j}, x_1^{j+1}) j = 3, \ldots, 2n + 1$ and hence $cost_1(2) = cost_2(2) = 2$, $cost_1(j) = cost_2(j) = 1$ $j = 3, \ldots, 2n + 1$.

$$d(SOL) = 10n + 4, WOR(J_{2n+1}) = 8n + 3, OPT(J_{2n+1}) = 12n + 4$$

Thus, we obtain $\delta_{\text{loc.change}\, HPP,e}(J_{2n+1}) = \frac{1}{2}$.

For the standard ratio, we deduce new improved results from lemma (1.5) and from theorem (3.3):

Corollary 4.2 We have the following results:

- Max $HPP_{s,t}$ is $\frac{1}{2}$-standard approximable and Max $HPP_{s,t}[a, 2a]$ is $\frac{3}{2}$-standard approximable.
- Min $HPP_{s,t}[a, 2a]$ is $\frac{3}{2}$-standard approximable.

4.2 The algorithm for one specified endpoint version

We propose an algorithm which differs from the one previously studied since we explicitly compute several solutions. Our algorithm is based upon a simple idea and uses structural properties of solutions. It still works by finding a maximum weight 2-matching containing specified edges and then discarding some edges and arbitrarily connecting the resulting paths to form an Hamiltonian path from $s$. The principle of our algorithm is to generate not only one but several feasible solutions following this method.

Consider a maximum weight 2-matching $M_r$ among those containing $(s, r)$, including elementary cycles $\Gamma_i, i = 1, \ldots, k$. In order to do that, we substitute $|V|d_{max} + 1$ for the cost of $(s, r)$ and we compute a maximum 2-matching in this new graph. Finally, for each cycle $\Gamma_i$, we consider four consecutive vertices $x_i^1, x_i^2, x_i^3, x_i^4$. Remark that we have numbered vertices such that $x_i^1 = r$ and $x_i^2 = s$. Moreover, if $|\Gamma_i| = 3$ then $x_i^3 = x_i^1$. For the last cycle $\Gamma_k$, we consider an additional vertex $y$ which is the other neighbor of $x_k^1$ in $\Gamma_k$. Thus, if $|\Gamma_k| = 4$ then $y = x_k^4$ while $y$ is a new vertex in the other case.
build sol1 = (Mr \ S1) U \{(x_1', x_2'), (x_2', x_3')\} U_j=1^{(k-1)/2} \{(x_2^{j-1}, x_2^j, x_3^{j+1}), (x_2^{j+1}, x_3^{j+2})\} \\
(sol_1 \text{ is a Hamiltonian path from } s \text{ to } r) \\
S_2 = U_j=2^{(k-1)} \{(x_1', x_2'), \{y, x_1'\}, \{(s, r)\} \} \\
obuild sol2 = (Mr \ S2) U \{(x_1', x_2'), U_j=1^{(k-1)/2} \{(x_2^{j-1}, x_2^j, x_3^{j+1}), (x_2^{j+1}, x_3^{j+2})\} \\
(sol_2 \text{ is a Hamiltonian path from } s \text{ to } y) \\
S_3 = U_j=1^{(k-1)} \{(x_2', x_3'), \{(x_2', x_3'), \{(s, r)\} \} \} \\
obuild sol3 = (Mr \ S3) U \{(x_2', x_3'), (x_3', x_3') \} U_j=1^{(k-1)/2} \{(x_2^{j-1}, x_2^j, x_3^{j+1}), (x_2^{j+1}, x_3^{j+2})\} \\
(sol_3 \text{ is a Hamiltonian path from } s \text{ to } r) \\
End if; \\
if k is odd then \\
S_1 = U_j=1^{(k-1)} \{(x_2', x_3'), \{(s, r)\} \} \\
obuild sol1 = (Mr \ S1) U \{(x_2', x_3'), U_j=1^{(k-1)/2} \{(x_2^{j-1}, x_2^j, x_3^{j+1})\} \\
(sol_1 \text{ is a Hamiltonian path from } s \text{ to } r) \\
S_2 = \{(s, r)\} U_j=2^{(k-1)} \{(x_1', x_2'), \{(s, r)\} \} \\
obuild sol2 = (Mr \ S2) U_j=1^{(k-1)/2} \{(x_2^{j-1}, x_2^j, x_3^{j+1})\} \\
(sol_2 \text{ is a Hamiltonian path from } s \text{ to } x_1') \\
S_3 = U_j=1^{(k-1)} \{(x_2', x_3'), \{(s, r)\} \} \\
obuild sol3 = (Mr \ S3) U \{(x_2', x_3'), \{(s, r)\} \} U_j=1^{(k-1)/2} \{(x_2^{j-1}, x_2^j, x_3^{j+1})\} \\
(sol_3 \text{ is a Hamiltonian path from } s \text{ to } r) \\
End if; \\
SOLr = \text{argmax}\{d(sol_1), d(sol_2), d(sol_3)\}; \\
End for r; \\
SOL = \text{argmax}\{d(SOLr) : r \in V \setminus \{s\}\}; \\

Observe that for any r, the solutions sol_1, sol_2 and sol_3 are Hamiltonian paths (from s to different endpoints) since the additional edges are adjacent to the ones substituted. The time-complexity of this algorithm is greater than the time-complexity of the previous algorithm but remains polynomial since the computation of the 2-matching problem is polynomial.

**Theorem 4.3** The algorithm [Patching 2-matching] is a \(\frac{2}{3}\)-differential approximation for Max HPP, and this ratio is tight.

**Proof:** Let \(I = (K_n, s, d)\) be an instance and let SOL^* be an optimal Hamiltonian path from s to \(r^*\). We denote \(loss_i, i = 1, 2, 3\), the quantity \(d(sol_i) - d(Mr^*) + d(s, r^*)\). Obviously, \(loss_i \leq 0\) and we have

\[
d(SOL) \geq d(SOL^*) \geq d(Mr^*) - d(s, r^*) + \frac{1}{3}(loss_1 + loss_2 + loss_3) \tag{4.4}\]

Moreover, the following structural property holds:

\[
SOL = U_j=1,2,3(sol_j \setminus Mr^*) \setminus (S1 \cup S2 \cup S3) \text{ is a Hamiltonian path starting from } s
\]

\[
d(SOL^*) = d(Mr^*) - d(s, r^*) + loss_1 + loss_2 + loss_3 \text{ since } d(sol_j \setminus Mr^*) = loss_j + d(Sj) - d(s, r^*) \text{ and } d(Mr^* \setminus (S1 \cup S2 \cup S3)) = d(Mr^*) - d(S1) - d(S2) - d(S3) + 2d(s, r^*). \text{ Hence, we deduce}
\]

\[
WOR(I) \leq d(Mr^*) - d(s, r^*) + loss_1 + loss_2 + loss_3 \tag{4.5}\]

Since SOL^* \{s, r^*\} is a particular 2-matching containing \(s, r^*\), we have

\[
OPT(I) \leq d(Mr^*) - d(s, r^*) \tag{4.6}\]

\[
9
\]
Finally, combining (4.4), (4.5) and (4.6) we obtain:

\[ d(SOL) \geq \frac{1}{3} WOR(I) + \frac{2}{3} OPT(I) \]

To show that the bound is approachable, consider the following instances. Let \( I_n = (K, s, d) \) be an instance defined by: \( V = \{ x_i^j : 1 \leq i \leq 3, 1 \leq j \leq 2n+1 \} \) with \( x_1^1 = s, d(x_2^j, x_2^j) = d(x_3^j, x_3^j) = d(x_1^1, x_3^j) = 2, \forall j = 1, \ldots, 2n+1 \) and \( d(x_1^j, x_3^{j+1}) = 2, \forall j = 1, \ldots, 2n \). Let the cost of all other edges be one. We have:

\[ d(SOL) \leq 10n + 4, \quad OPT(I_n) = 12n + 4, \quad WOR(I_n) = 6n + 2 \]

leading to the conclusion \( \lim \delta_{2\text{-matching}}(I_n) \leq \frac{2}{3} \).

For the standard ratio, we deduce new improved results from theorem (3.3):

**Corollary 4.4** We have the following results:

- Max Hop is \( \frac{2}{3} \)-standard approximable and Max HOPs[a, 2a] is \( \frac{3}{5} \)-standard approximable.
- Min Hop is \( \frac{2}{3} \)-standard approximable.

5 Towards thresholds of differential non-approximation

A useful technique to establish some standard non-approximation thresholds of NP-hard problems consists in establishing the fact that they are not simple. Recall that an NPO problem is called simple if there exists a polynomial time algorithm such that, for any fixed integer \( k \), \( OPT(I) \leq k \) can be resolved within polynomial time. So, we can also prove a standard non-approximation threshold equal to \( 2/3 \) for the Bin-Packing problem because its restriction to instances verifying \( OPT(I) \leq 2 \) is still a NP-hard problem. Similarly, we will say that \( \pi \) is \( \delta \)-simple if its restriction \( \pi_k \) to instances verifying for any integer \( k \), \( |WOR(I) - OPT(I)| \leq k \) can be solved within polynomial time. Thus, we also have the following proposition:

**Proposition 5.1** If \( \pi \in PTAS(\delta) \), then \( \pi \) is \( \delta \)-simple.

**Proof:** Start from a problem \( \pi \in NPO \) and build the problem \( \phi(\pi) \) defined by:

if \( \pi = (D, sol, m, Triv, goal) \) then \( \phi(\pi) = (D, sol, m', Triv, Maz) \) where \( m'(I, x) = |WOR(I) - m[I, x]| \).

If we use the result of [25] for the standard ratio since we have that \( r(\phi(\pi))(I, x) = \delta[I, x] \).

In other words, problems which are not \( \delta \)-simple do not admit differential approximation scheme and are even hard to establish a differential non-approximation threshold; thus, if the sub-problem verifying \( |WOR(I) - OPT(I)| \leq 1 \) can be solved within polynomial time, then any \( \varepsilon \)-approximation algorithm can guarantee a differential approximation ratio greater than, equal to \( \frac{K_0}{K_0 + 1} + \varepsilon \) for \( \pi \). The proposition above allows to achieve a hardness threshold given by \( K_0 \). We conjecture that HOP is \( \delta \)-simple for small values of \( K_0 \). If this was true, the threshold of proposition (3.5) could be meaningfully improved. Anyway, that will allow us to better identify the space of feasible solutions and to understand how we can (or not) polynomially navigate in it.

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\( ^{\text{*}} \)Observe that the problem \( \phi(\pi) \) is not in NPO anymore when \( WOR(I) \) is not computable in polynomial time, which is the case in this paper.
References


