

A Fully Polynomial Time Approximation Scheme for Packing While Traveling

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Abstract

Understanding the interactions between different combinatorial optimisation problems in real-world applications is a challenging task. Recently, the traveling thief problem (TTP), as a combination of the classical traveling salesperson problem and the knapsack problem, has been introduced to study these interactions in a systematic way. We investigate the underlying non-linear packing while traveling (PWT) problem of the TTP where items have to be selected along a fixed route. We give an exact dynamic programming approach for this problem and a fully polynomial time approximation scheme (FPTAS) when maximising the benefit that can be gained over the baseline travel cost. Our experimental investigations show that our new approaches outperform current state-of-the-art approaches on a wide range of benchmark instances.

Introduction

Combinatorial optimisation problems play a crucial role in important areas such as planning, scheduling and routing. Many combinatorial optimisation problems have been studied extensively in the literature. Two of the most prominent ones are the traveling salesperson problem (TSP) and the knapsack problem (KP) and numerous high performing algorithms have been designed for these two problems.

Looking at combinatorial optimisation problems arising in real-world applications, one can observe that real-world problems often are composed of different types of combinatorial problems. For example, delivery problems usually consists of a routing

part for the vehicle(s) and a packing part of the goods onto the vehicle(s). Recently, the traveling thief problem (TTP) [1] has been introduced to study the interactions of different combinatorial optimisation problems in a systematic way and to gain better insights into the design of multi-component problems. The TTP combines the TSP and KP by making the speed that a vehicle travels along a TSP tour dependent on the weight of the selected items. Furthermore, the overall objective is given by the sum of the profits of the collected items minus the weight dependent travel cost along the chosen route. A wide range of heuristic search algorithms [2, 3, 8] and a large benchmark set [12] have been introduced for the TTP in recent years. However, up to now there are no high performing exact approaches to deal with the TTP.

The study of non-linear planning problems is an important topic and the design of approximation algorithms has gained increasing interest in recent years [6, 14]. The non-linear packing while traveling problem (PWT) has been introduced in [10] to push forward systematic studies on multi-component problems and deals with the packing part combined with the non-linear travel cost function of the TTP. The PWT can be seen as the TTP when the route is fixed but the cost still depends on the weight of the items on the vehicle. The problem is motivated by gaining advanced precision when minimising transportation costs that may have non-linear nature, for example, in applications where weight impacts the fuel costs [4, 7]. From this point of view, the PWT is a baseline problem in various vehicle routing problems with non-linear costs. Some specific applications of the PWT may deal with a single truck collecting goods in large remote areas without alternative routes, that is a single main route that a vehicle has to follow may exist while any deviations from it in order to visit particular cities are negligible [11]. The problem is \mathcal{NP} -hard even without the capacity constraint usually imposed on the knapsack. Furthermore, exact and approximative mixed integer programming approaches as well as a branch-infer-and-bound approach [11] have been developed for this problem.

We introduce a dynamic programming approach for PWT. The key idea is to consider the items in the order they appear on the route that needs to be travelled and apply dynamic programming similar as for the classical knapsack problem [13]. When considering an item, the decision has to be made on whether or not to pack the item. The dynamic programming approach computes for the first i , $1 \leq i \leq m$, items and each possible weight w the maximal objective value that can be obtained. As the programming table that is used depends on the number of different possible weights, the algorithm runs in pseudo-polynomial time.

After having obtained the exact approach based on dynamic programming, we consider the design of a fully polynomial approximation scheme (FPTAS) [5].

First, we show that it is \mathcal{NP} -hard to decide whether a given instance of PWT has a non-negative objective value. This rules out any polynomial time algorithm with finite approximation ratio under the assumption $P \neq NP$. Due to this, we design a FPTAS for the amount that can be gained over the travel cost when the vehicle travels empty (which is the minimal possible travel cost). Our FPTAS makes use of the observation that the item with the largest benefit leads to an objective value of at least OPT/m and uses appropriate rounding in the previously designed dynamic programming approach.

We evaluate our two approaches on a wide range of instances from the TTP benchmark set [12] and compare it to the exact and approximative approaches given in [11].

Our results show that the large majority of the instances that can be handled by exact methods, are solved much quicker by dynamic programming than the previously developed mixed integer programming and branch-infer-and-bound approaches. Considering instances with a larger profit and weight range, we show that the choice of the approximation guarantee significantly impacts the runtime behaviour.

The paper is structured as follows. In Section 2, we introduce the problem. We present the exact dynamic programming approach in Section 3 and design a FPTAS in Section 4. Our experimental results are shown in Section 5. Finally, we finish with some conclusions.

Problem Statement

The PWT can be formally defined as follows. Given are $n + 1$ cities, distances d_i , $1 \leq i \leq n$, from city i to city $i + 1$, and a set of items M , $|M| = m$, distributed all over the first n cities. W.l.o.g., we assume $m = \Omega(n)$ to simplify our notations. Each city i , $1 \leq i \leq n$, contains a set of items $M_i \subseteq M$, $|M_i| = m_i$. Each item $e_{ij} \in M_i$, $1 \leq j \leq m_i$, is characterised by its positive integer profit p_{ij} and weight w_{ij} .

In addition, a fixed route $N = (1, 2, \dots, n + 1)$ is given that is traveled by a vehicle with velocity $v \in [v_{min}, v_{max}]$. Let $x_{ij} \in \{0, 1\}$ be a variable indicating whether or not item e_{ij} is chosen in a solution. Then a set $S \subseteq M$ of selected items can be represented by a decision vector $x = (x_{11}, x_{12}, \dots, x_{1m_1}, x_{21}, \dots, x_{nm_n})$. The total benefit of selecting a subset of items S is calculated as

$$B(x) = P(x) - R \cdot T(x),$$

where

$$P(x) = \sum_{i=1}^n \sum_{j=1}^{m_i} p_{ij} x_{ij}$$

represents the total profit of selected items and

$$T(x) = \sum_{i=1}^n \frac{d_i}{v_{max} - \nu \sum_{k=1}^i \sum_{j=1}^{m_k} w_{kj} x_{kj}}$$

is the total travel time for the vehicle carrying these items.

Here, $\nu = \frac{v_{max} - v_{min}}{W}$ is the constant defined by the input parameters, where W is the capacity of the vehicle. $T(x)$ has the following interpretation: when the vehicle is traveling from city i to city $i + 1$, the selected items have to be carried and the maximal speed v_{max} of the vehicle is reduced by a normalised amount that depends linearly on the weight of these items. Because the velocity is influenced by the weight of collected items, the total travel time increases along with their weight. Given a renting rate $R \in (0, \infty)$, $R \cdot T(x)$ is the total cost of carrying the items chosen by x . The objective of this problem is to find a solution $x^* = \arg \max_{x \in \{0,1\}^m} B(x)$.

We investigate dynamic programming and approximation algorithms [5] for the non-linear packing while traveling problem. A FPTAS for a given maximisation problem is an algorithm A that obtains for any valid input I and ϵ , $0 < \epsilon \leq 1$, a solution of objective value $A(I) \geq (1 - \epsilon)OPT(I)$ in time polynomial in the input size $|I|$ and $1/\epsilon$.

Dynamic Programming

We introduce a dynamic programming approach for solving the PWT. Dynamic programming is one of the traditional approaches for the classical knapsack problem [13]. The dynamic programming table β consists of W rows and m columns. Items are processed in the order they appear along the path N and we consider them in the lexicographic order with respect to their indices, i.e.

$$e_{ab} \preceq e_{ij}, \text{ iff } ((a < i) \vee (a = i \wedge b \leq j)).$$

Note that \preceq is a total strict order and we process the items in this order starting with the smallest element. The entry $\beta_{i,j,k}$ represents the maximal benefit that can be obtained by considering all combinations of items e_{ab} with $e_{ab} \preceq e_{ij}$ leading to weight exactly k . We denote by $\beta(i, j, \cdot)$ the column containing the entries $\beta_{i,j,k}$. In the case that a combination of weight k doesn't exist, we set $\beta_{i,j,k} = -\infty$. We denote by

$$d_{in} = \sum_{l=i}^n d_l$$

the distance from city i to the last city $n + 1$.

We denote by $B(\emptyset)$ the benefit of the empty set which is equivalent to the travel cost when the vehicle travels empty. Furthermore, $B(e_{ij})$ denotes the benefit when only item e_{ij} is chosen.

For the first item e_{ij} according to \preceq , we set

$$\beta(i, j, 0) = B(\emptyset),$$

$$\beta(i, j, w_{ij}) = B(e_{ij}),$$

and

$$\beta(i, j, k) = -\infty \text{ iff } k \notin \{0, w_{ij}\}.$$

Let $e_{i'j'}$ be the predecessor of item e_{ij} in \preceq . Based on $\beta(i', j', \cdot)$ we compute for $\beta(i, j, \cdot)$ each entry $\beta_{i,j,k}$ as

$$\max \begin{cases} \beta_{i',j',k} \\ \beta_{i',j',k-w_{ij}} + p_{ij} - Rd_{in} \left(\frac{1}{v_{max} - \nu k} - \frac{1}{v_{max} - \nu(k-w_{ij})} \right) \end{cases}$$

Let e_{st} be the last element according to \preceq , then $\max_k \beta(s, t, k)$ is reported as the value of an optimal solution. We now investigate the runtime for this dynamic program. If d_{in} has been computed for each i , $1 \leq i \leq n - 1$, which takes $O(n)$ time in total, then each entry can be compute in constant time.

Theorem 1. *The entry $\beta(i, j, k)$ stores the maximal possible benefit for all subsets of $I_{ij} = \{e_{ab} \mid e_{ab} \preceq e_{ij}\}$ having weight k .*

Proof. The proof is by induction. The statement is true for the first item e_{ij} according to \preceq as there are only the two options of choosing or not choosing e_{ij} . Assume that $\beta(i', j', k)$ stores the maximal benefit for each weights k when considering all items of $I_{i'j'}$. There two options exist when we consider item e_{ij} in addition: to include or not include e_{ij} . If e_{ij} is not included, then the best possible value for $\beta(i, j, k)$ is $\beta(i', j', k)$. If e_{ij} is included, then remaining weight has to come from the previous items whose maximal benefit has been $\beta(i', j', k - w_{ij})$. Transporting a set of items of weight $k - w_{ij}$ from city i to city $n + 1$ has cost

$$\frac{Rd_{in}}{v_{max} - \nu(k - w_{ij})}$$

and transporting a set of items of weight k from city i to $n + 1$ has cost

$$\frac{Rd_{in}}{v_{max} - \nu k}.$$

This cost of transporting items of a fixed weight from city i to city $n + 1$ is independent of the choice of items. Therefore, $\beta(i, j, k)$ stores the maximal possible benefit when considering all possible subsets of $I_{ij} = \{e_{ab} \mid e_{ab} \preceq e_{ij}\}$ having weight k . \square

To speed up the computation of our DP approach, we only store an entry for $\beta(i, j, k)$ if it is not dominated by any other entry in $\beta(i, j, \cdot)$, i.e. there is no other entry $\beta(i, j, k')$ with $\beta(i, j, k') \geq \beta(i, j, k)$ and $k' < k$. This does not affect the correctness of the approach as an item e_{ij} can be added to any entry of $\beta(i', j', \cdot)$ and therefore we obtain for each dominated entry at least one entry in the last column having at least the same benefit but potentially smaller weight.

Approximation Algorithms

We now turn our attention to approximation algorithms. The NP-hardness proof for PWT given in [11] does not rule out polynomial time approximation algorithms. In this section, we first show that polynomial time approximation algorithms with a finite approximation ratio do not exist under the assumption $P \neq NP$. This motivates the design of a FPTAS for the amount that can be gained over the baseline cost when the vehicle is traveling empty.

Inapproximability of PWT

The objective function for PWT can take on positive and negative values. We show that deciding whether a given PWT instances has a solution that is non-negative is already NP-complete.

Theorem 2. *Given a PWT instance, the problem to decide whether there is a solution x with $B(x) \geq 0$ is NP-complete.*

Proof. The problem is in NP as one can verify in polynomial time for a given solution x whether $B(x) \geq 0$ holds by evaluating the objective function. It remains to show that the problem is NP-hard.

We address two cases: when $B(x)$ is subject to the capacity constraint and when it is unconstrained. In both cases, we reduce the \mathcal{NP} -complete *subset sum problem* (SSP) to the decision variant of PWT which asks whether there is a solution with objective value at least 0. The input for SSP is given by m positive integers $S = \{s_1, \dots, s_m\}$ and a positive integer Q . The question is whether there exists a vector $x \in \{0, 1\}^m$ such that $\sum_{k=1}^m s_k x_k = Q$. We encode the instance of SSP given by S and Q as the instance of PWT, which consists of two cities. The first city contains all the m items and the distance between the cities is $d_1 = 1$. We assume that $p_{1k} = w_{1k} = s_k$, $1 \leq k \leq m$.

To prove the first case, we construct the instance I' of PWT. We extend the initial settings by giving to the vehicle capacity $W = Q$ and define its velocity range as $v_{max} = 2$ and $v_{min} = 1$. Furthermore, we set $R^* = Q$. Consider the nonlinear function $f'_{R^*} : [0, W] \rightarrow \mathbb{R}$ defined as

$$f'_{R^*}(w) = w - \frac{R^*}{2 - w/W} = w - \frac{Q}{2 - w/Q}.$$

f'_{R^*} , which is defined on the interval $[0, W]$, is a continuous concave function that reaches its unique maximum of 0 in the point $w^* = W = Q$, i.e. $f'_{R^*}(w) < 0$ for $w \in [0, W]$ and $w \neq w^*$. Then 0 is the maximum value for f'_{R^*} when being restricted to integer input, too. Therefore, the objective function for PWT is given by

$$g'_{R^*}(x) = \sum_{k=1}^m p_{1k} x_k - \frac{R^*}{2 - \frac{1}{W} \sum_{k=1}^m w_{1k} x_k}.$$

There exists an $x \in \{0, 1\}^m$ such that $g'_{R^*}(x) \geq 0$ iff

$$\sum_{k=1}^m s_k x_k = \sum_{k=1}^m w_{1k} x_k = \sum_{k=1}^m p_{1k} x_k = Q.$$

Therefore, the instance of SSP has answer YES iff the optimal solution of the PWT instance I' has objective value at least 0. Obviously, the reduction can be carried out in polynomial time which completes the proof of the first case.

To prove the second case, we construct the instance I'' of PWT where our settings assume

$$W = \sum_{k=1}^m s_k$$

and

$$v_{min} = \sqrt{Q/(2W - Q)} = v_{max}/2.$$

We then set

$$R^* = v_{min} \cdot W (v_{max} - v_{min} \cdot Q/W)^2.$$

Finally, this gives us the functions $f''_{R^*}(w)$ and $g''_{R^*}(x)$ of the following forms:

$$f''_{R^*}(w) = w - \frac{R^*}{v_{max} - v_{min} \cdot w/W}.$$

$$g''_{R^*}(x) = \sum_{k=1}^m p_{1k}x_k - \frac{R^*}{v_{max} - \frac{v_{min}}{W} \sum_{k=1}^m w_{1k}x_k}.$$

Similarly, there exists an $x \in \{0, 1\}^m$ such that $g''_{R^*}(x) \geq 0$ iff

$$\sum_{k=1}^m s_k x_k = \sum_{k=1}^m w_{1k} x_k = \sum_{k=1}^m p_{1k} x_k = Q.$$

Therefore, the instance of SSP has answer YES iff the optimal solution of the PWT instance I'' has objective value at least 0, while the reduction can be carried out in polynomial time. □

The objective function can take on negative and non-negative values. Theorem 2 rules out meaningful approximations for the original objective functions B and we state this in the following corollary.

Corollary 1. *There is no polynomial time approximation algorithm for PWT with a meaningful approximation ratio, unless $P=NP$.*

FPTAS for amount over baseline travel cost

As there are no polynomial time approximation algorithms for fixed approximation ratio for PWT, we consider the amount that can be gained over the cost when the vehicle travels empty as the objective. This is motivated by the scenario where the vehicle has to travel along the given route and the goal is to maximise the gain over this baseline cost. Note that an optimal solution for this objective is also an optimal solution for PWT. However, approximation results do not carry over to PWT as the objective values are “shifted” by the cost when traveling empty.

Let

$$B(\emptyset) = -R \cdot \sum_{i=1}^n d_i / v_{max}$$

be the travel cost (or benefit) for the empty truck. $B(\emptyset)$ can be seen as the set up cost that we have to pay at least. We consider the objective

$$B'(x) = B(x) - B(\emptyset),$$

i. e. for the amount that we can gain over this setup cost, and give an FPTAS. Note, that we have $-R \cdot T(x) \leq B(\emptyset)$ for any $x \in \{0, 1\}^m$ and $P(x) - R \cdot T(x) - B(\emptyset) = 0$ if $x = 0^m$.

We now give a FPTAS for the amount that can be gained over the cost when the vehicle travels empty and denote by OPT the optimal value for this objective, i.e.

$$OPT = \max_{x \in \{0, 1\}^m} B'(x).$$

Algorithm 1 FPTAS for $B'(x)$

- Set $L = \max_{e_{ij} \in M} B'(e_{ij})$, $r = \epsilon L/m$, and $d_{in} = \sum_{l=i}^n d_l$, $1 \leq i \leq n$.
 - Compute order \preceq on the items e_{ij} by sorting them in lexicographic order with respect to their indices (i, j) .
 - For the first item e_{ij} according to \preceq , set $\beta(i, j, 0) = B'(\emptyset)$ and $\beta(i, j, w_{ij}) = B'(e_{ij})$.
 - Consider the remaining items of M in the order of \preceq and do for each item e_{ij} and its predecessor $e_{i'j'}$:
 - In increasing order of k do for each $\beta(i', j', k)$ with $\beta(i', j', k) \neq -\infty$
 - * If there is no $\beta(i, j, k')$ with $(\lfloor \beta(i, j, k')/r \rfloor \geq \lfloor \beta(i', j', k)/r \rfloor$ and $k' < k$),
set $\beta(i, j, k) = \max\{\beta(i, j, k), \beta(i', j', k)\}$.
 - * If there is no $\beta(i, j, k')$ with $(\lfloor \beta(i, j, k')/r \rfloor \geq \lfloor \beta(i', j', k + w_{ij})/r \rfloor$ and $k' < k + w_{ij}$),
set $\beta(i, j, k + w_{ij}) = \max\{\beta(i, j, k + w_{ij}), \beta(i', j', k) + p_{ij} + Rd_{in}(\frac{1}{v_{\max} - \nu k} - \frac{1}{v_{\max} - \nu(k + w_{ij})})\}$.
-

Considering the dynamic program for $B'(x)$ instead of $B(x)$ increases each entry by $|B(\emptyset)|$ and therefore obtains an optimal solution for $B'(x)$ in pseudo-polynomial time. In order to obtain an FPTAS, we round the values of $B'(x)$ and store for each rounded value only the minimal achievable weight.

Let

$$t(w) = \frac{1}{v_{\max} - \nu w}$$

denote the travel time per unit distance when traveling with weight w . We have $t(x + w) - t(x) \geq t(w)$ for any $x \geq 0$ as $t(w)$ is a convex function.

Consider the value $B(e_{ij}) - B(\emptyset)$ which gives the additional amount over $B(\emptyset)$ when only packing item e_{ij} . We assume that there exists at least one item e_{ij} with $B(e_{ij}) - B(\emptyset) > 0$ as otherwise $OPT = 0$ the solution being $\{0\}^m$. Let $P(e_{ij})$ and $T(e_{ij})$ be the profit and travel time when only choosing item e_{ij} . Furthermore, let $x^* = \arg \max_{x \in \{0,1\}^m} B'(x)$ be an optimal solution of value $OPT > 0$.

We have

$$\sum_{i=1}^n \sum_{j=1}^{m_i} (P(e_{ij}) - R \cdot T(e_{ij})) x_{ij}^* - B(\emptyset) \geq B(x^*) - B(\emptyset) = OPT$$

as $t(w)$ is monotonically increasing and convex.

Therefore the item e_{ij} of x^* with $B(e_{ij}) - B(\emptyset) > 0$ maximal fulfils $B(e_{ij}) - B(\emptyset) \geq OPT/m$.

Let

$$L = \max_{e_{ij} \in M} B'(e_{ij}) > 0$$

be maximal possible objective value when choosing exactly one item. We have

$$L \geq OPT/m \text{ and } L \leq OPT.$$

We set $r = \epsilon L/m$, where ϵ is the approximation parameter for the FPTAS. For the FPTAS we round $B'(x)$ to $\lfloor (B'(x)/r) \rfloor$ and store for each of such values the minimal weight obtained. As we only store entries with $0 \leq B'(x) \leq OPT$, and for each such integer based on dominance and rounding one entry, the total number of entries per column is upper bounded by

$$(OPT/r) + 1 \leq OPT/(\epsilon L/m) + 1 \leq m^2/\epsilon + 1$$

and number of entries in the dynamic programming table is $O(m^3/\epsilon)$.

In each step, we make an error of at most

$$r = \epsilon L/m \leq \epsilon OPT/m$$

and the error after m steps is at most $\epsilon L \leq \epsilon OPT$. Hence, the solution x with maximal B' -value after having considered all items fulfils

$$B'(x) \geq (1 - \epsilon)OPT.$$

To implement the idea (see Algorithm 1), we only store an entry $\beta(i, j, k)$ if there is no entry $\beta(i, j, k')$ with

$$\lfloor \beta(i, j, k')/r \rfloor \geq \lfloor \beta(i, j, k)/r \rfloor \text{ and } k' < k.$$

Hence, for each possible value $\lfloor \beta(i, j, k)/r \rfloor$ at most one entry is stored and the number of entries for each column $\beta(i, j, \cdot)$ is upper bounded by $m^2/\epsilon + 1$ (as stated above). Using for each $\beta(i, j, \cdot)$ a list which stores the entries $\beta(i, j, k)$ in increasing order of k can be used for our implementation.

Based on our investigations and the design of Algorithm 1, we can state the following result.

Theorem 3. *Algorithm 1 is a fully polynomial time approximation scheme (FPTAS) for the objective B' . It obtains for any ϵ , $0 < \epsilon \leq 1$, a solution x with $B'(x) \geq (1 - \epsilon) \cdot OPT$ in time $O(m^3/\epsilon)$.*

The construction of the FPTAS only used the fact that the travel time per unit distance is monotonically increasing and convex. Hence, the FPTAS holds for any PWT problem where the travel time per unit distance has this property.

Experiments and Results

In this section, we investigate the effectiveness of the proposed DP and FPTAS approaches based on our implementations in Java¹. We mainly focus on two issues: 1) studying how the DP and FPTAS perform compared to the state-of-the-art approaches; 2) investigating how the performance and accuracy of the FPTAS change when the parameter ϵ is altered.

¹The code will be made available online at time of publication.

Table 1: Results on Small Range Instances

Instance	m	OPT	Exact Approaches			Approximation Approaches											
			exactMIP	BIB	DP	approxMIP		FPTAS									
			RT(s)	RT(s)	RT(s)	AR(%)	RT(s)	$\epsilon = 0.0001$		$\epsilon = 0.01$		$\epsilon = 0.1$		$\epsilon = 0.25$		$\epsilon = 0.75$	
instance family <code>eil101</code>																	
uncorr_01	100	1651.6970	1.217	5.694	0.027	100.0000	3.838	100.0000	0.001	100.0000	0.001	100.0000	0.001	100.0000	0.001	100.0000	0.025
uncorr_06	100	10155.4942	12.605	3.698	0.065	100.0000	4.961	100.0000	0.012	100.0000	0.011	100.0000	0.011	100.0000	0.011	99.9928	0.063
uncorr_10	100	10297.7134	3.525	0.795	0.036	100.0000	0.624	100.0000	0.017	100.0000	0.017	99.9939	0.016	99.9939	0.016	99.9653	0.037
uncorr-s-w_01	100	2152.6188	0.328	7.566	0.001	100.0000	3.978	100.0000	0.000	100.0000	0.000	100.0000	0.000	100.0000	0.000	100.0000	0.003
uncorr-s-w_06	100	4333.8512	12.590	2.215	0.012	100.0000	2.699	100.0000	0.008	100.0000	0.007	100.0000	0.007	99.9569	0.008	99.9569	0.017
uncorr-s-w_10	100	9048.4908	37.144	1.107	0.022	100.0000	1.763	100.0000	0.012	100.0000	0.012	100.0000	0.012	100.0000	0.013	99.9355	0.020
b-s-corr_01	100	4441.9852	1.420	125.954	0.014	100.0000	5.366	100.0000	0.010	100.0000	0.009	100.0000	0.009	100.0000	0.008	100.0000	0.013
b-s-corr_06	100	10260.9767	4.509	22.541	0.101	100.0000	2.761	100.0000	0.058	100.0000	0.057	100.0000	0.048	100.0000	0.043	100.0000	0.087
b-s-corr_10	100	13630.6153	11.013	27.081	0.187	99.9971	3.713	100.0000	0.103	100.0000	0.101	99.9971	0.081	99.9606	0.065	99.8143	0.113
uncorr_01	500	17608.5781	19.594	27.581	0.247	100.0000	5.757	100.0000	0.171	100.0000	0.161	100.0000	0.153	100.0000	0.163	100.0000	0.377
uncorr_06	500	56294.5239	384.213	13.354	2.829	100.0000	7.800	100.0000	2.370	100.0000	2.344	100.0000	2.300	100.0000	2.212	100.0000	2.340
uncorr_10	500	66141.4840	211.302	2.325	4.010	100.0000	0.718	100.0000	3.720	100.0000	3.645	100.0000	3.446	100.0000	3.531	100.0000	3.632
uncorr-s-w_01	500	13418.8406	4.337	34.866	0.090	100.0000	50.310	100.0000	0.085	100.0000	0.090	100.0000	0.084	100.0000	0.087	99.9910	0.085
uncorr-s-w_06	500	34280.4730	346.430	7.285	1.040	100.0000	9.609	100.0000	0.964	100.0000	0.933	100.0000	0.905	100.0000	0.936	100.0000	0.920
uncorr-s-w_10	500	50836.6588	519.902	3.338	2.022	100.0000	3.354	100.0000	2.005	100.0000	1.783	100.0000	1.753	100.0000	1.784	100.0000	2.147
b-s-corr_01	500	21306.9158	40.482	624.204	1.534	100.0000	13.338	100.0000	1.373	100.0000	1.279	100.0000	1.116	100.0000	0.949	100.0000	0.716
b-s-corr_06	500	69370.2367	236.387	97.313	14.616	99.9996	7.847	100.0000	13.393	100.0000	12.975	100.0000	11.642	99.9996	9.741	99.9996	6.018
b-s-corr_10	500	82033.9452	376.569	218.728	22.011	100.0000	2.309	100.0000	21.372	100.0000	20.829	100.0000	18.573	100.0000	15.313	99.9943	8.840
uncorr_01	1000	36170.9109	218.306	114.567	1.872	99.9993	11.918	100.0000	1.891	100.0000	1.875	100.0000	1.832	100.0000	1.845	100.0000	1.764
uncorr_06	1000	93949.1981	1261.949	36.847	20.944	100.0000	17.971	100.0000	17.024	100.0000	16.615	100.0000	16.545	100.0000	16.378	100.0000	15.713
uncorr_10	1000	122963.6617	620.896	4.821	30.116	100.0000	2.184	100.0000	27.305	100.0000	26.783	100.0000	26.541	100.0000	26.051	100.0000	23.905
uncorr-s-w_01	1000	27800.9614	241.957	399.158	0.802	100.0000	4985.566	100.0000	0.730	100.0000	0.690	100.0000	0.688	100.0000	0.724	100.0000	0.687
uncorr-s-w_06	1000	61764.4599	1152.624	12.792	9.872	100.0000	19.063	100.0000	8.686	100.0000	8.812	100.0000	8.560	100.0000	8.740	100.0000	8.396
uncorr-s-w_10	1000	103572.4074	2146.408	7.644	15.047	100.0000	9.688	100.0000	14.030	100.0000	13.912	100.0000	13.797	100.0000	13.982	100.0000	13.492
b-s-corr_01	1000	46886.1094	378.551	6129.531	11.783	99.9988	46.394	100.0000	11.714	100.0000	11.358	100.0000	10.793	100.0000	9.592	100.0000	6.536
b-s-corr_06	1000	125830.6887	643.533	919.201	94.523	99.9999	10.311	100.0000	92.411	100.0000	91.039	100.0000	83.002	99.9999	71.078	100.0000	45.433
b-s-corr_10	1000	161990.5015	862.572	1646.520	151.601	100.0000	7.160	100.0000	150.279	100.0000	149.722	100.0000	134.764	100.0000	113.049	99.9981	70.135

Table 2: Results of DP and FPTAS on Large Range Instances

Instance	m	DP		FPTAS											
		OPT	RT(s)	$\epsilon = 0.0001$	$\epsilon = 0.001$	$\epsilon = 0.01$	$\epsilon = 0.1$	$\epsilon = 0.25$	$\epsilon = 0.5$	$\epsilon = 0.75$					
				AR(%)	RT(s)	AR(%)	RT(s)	AR(%)	RT(s)	AR(%)	RT(s)	AR(%)	RT(s)	AR(%)	RT(s)
instance family eil101_large-range															
uncorr_01	100	69802802.2801	0.030	100.0000	0.002	100.0000	0.002	100.0000	0.002	100.0000	0.002	100.0000	0.002	100.0000	0.029
uncorr_06	100	204813765.6933	0.053	100.0000	0.019	100.0000	0.020	100.0000	0.019	100.0000	0.019	100.0000	0.019	100.0000	0.049
uncorr_10	100	172176182.1249	0.041	100.0000	0.028	100.0000	0.028	100.0000	0.028	100.0000	0.028	100.0000	0.027	100.0000	0.037
uncorr-s-w_01	100	36420530.5753	0.006	100.0000	0.003	100.0000	0.003	100.0000	0.003	100.0000	0.003	100.0000	0.003	100.0000	0.004
uncorr-s-w_06	100	148058928.2952	0.098	100.0000	0.072	100.0000	0.502	100.0000	0.072	100.0000	0.069	100.0000	0.065	100.0000	0.070
uncorr-s-w_10	100	142538516.4602	0.136	100.0000	0.101	100.0000	0.104	100.0000	0.103	99.9978	0.096	99.9978	0.086	99.9978	0.089
m-s-corr_01	100	19549602.2671	0.003	100.0000	0.002	100.0000	0.002	100.0000	0.002	100.0000	0.002	100.0000	0.002	100.0000	0.002
m-s-corr_06	100	137203175.1921	0.147	100.0000	0.115	100.0000	0.118	100.0000	0.113	100.0000	0.089	100.0000	0.063	100.0000	0.043
m-s-corr_10	100	225584278.6004	0.424	100.0000	0.326	100.0000	0.329	100.0000	0.312	100.0000	0.200	100.0000	0.179	100.0000	0.073
uncorr_01	500	385692662.0930	0.470	100.0000	0.451	100.0000	0.454	100.0000	0.619	100.0000	0.508	100.0000	0.445	100.0000	0.517
uncorr_06	500	958013934.6172	3.539	100.0000	3.749	100.0000	7.431	100.0000	3.947	100.0000	3.690	99.9996	3.677	99.9996	3.021
uncorr_10	500	844949838.4389	4.870	100.0000	5.393	100.0000	5.716	100.0000	5.483	100.0000	5.135	100.0000	4.851	99.9992	4.295
uncorr-s-w_01	500	182418888.9364	1.157	100.0000	1.157	100.0000	1.199	100.0000	1.145	99.9995	1.112	99.9995	1.063	99.9995	0.929
uncorr-s-w_06	500	780432253.0187	22.390	100.0000	25.040	100.0000	26.276	100.0000	24.024	100.0000	23.282	99.9997	21.756	99.9997	18.411
uncorr-s-w_10	500	714433353.7957	30.959	100.0000	34.458	100.0000	39.004	100.0000	34.308	100.0000	32.308	99.9996	28.792	99.9990	25.971
m-s-corr_01	500	96463941.1275	2.335	100.0000	2.478	100.0000	2.782	100.0000	2.695	100.0000	1.509	100.0000	0.963	100.0000	0.408
m-s-corr_06	500	666701000.1488	108.705	100.0000	126.833	100.0000	139.630	100.0000	122.750	100.0000	62.479	100.0000	33.547	100.0000	10.642
m-s-corr_10	500	1082009880.5886	262.999	100.0000	299.862	100.0000	317.352	100.0000	274.284	100.0000	145.087	100.0000	78.470	99.9994	25.924
uncorr_01	1000	777386336.9660	4.222	100.0000	4.397	100.0000	4.347	100.0000	4.309	100.0000	4.341	100.0000	4.377	100.0000	4.240
uncorr_06	1000	1933319297.4248	46.043	100.0000	51.383	100.0000	53.087	100.0000	48.861	100.0000	52.957	99.9999	52.062	99.9997	51.488
uncorr_10	1000	1693797490.1704	64.485	100.0000	76.744	100.0000	78.847	100.0000	74.128	100.0000	82.754	100.0000	77.057	100.0000	72.567
uncorr-s-w_01	1000	361991311.8336	14.254	100.0000	15.072	100.0000	15.670	100.0000	14.523	100.0000	14.110	100.0000	14.039	100.0000	11.129
uncorr-s-w_06	1000	1574469459.3163	286.843	100.0000	318.096	100.0000	330.508	100.0000	337.289	100.0000	334.318	100.0000	307.588	99.9998	245.927
uncorr-s-w_10	1000	1439410696.3695	393.793	100.0000	438.775	100.0000	455.830	100.0000	464.527	100.0000	441.955	100.0000	433.672	99.9994	340.813
m-s-corr_01	1000	191170309.5684	46.858	100.0000	58.031	100.0000	59.987	100.0000	58.101	100.0000	31.703	100.0000	18.771	100.0000	6.831
m-s-corr_06	1000	1315708161.7720	2393.205	100.0000	2512.281	100.0000	2606.412	100.0000	1921.573	100.0000	666.749	100.0000	364.452	100.0000	150.060
m-s-corr_10	1000	2163713055.3759	6761.490	100.0000	6668.535	100.0000	6441.906	100.0000	4526.653	100.0000	1334.882	100.0000	703.258	100.0000	282.211

In order to be comparable to the mixed integer programming (MIP) and the branch-infer-and-bound (BIB) approaches presented in [11], we conduct our experiments on the same families of test instances. Our experiments are carried out on a computer with 4GB RAM and a 3.06GHz Intel Dual Core processor, which is also the same as the machine used in the paper mentioned above.

We compare the DP to the exact MIP (*exactMIP*) and the branch-infer-and-bound approaches as well as the FPTAS to the approximate MIP (*approxMIP*), as the former three are all exact approaches and the latter two are all approximations. Table 1 demonstrates the results for a route of 101 cities and various types of packing instances. For this particular family, we consider three types of instances: *uncorrelated* (uncorr), *uncorrelated with similar weights* (uncorr-s-w) and *bounded strongly correlated* (b-s-corr), which are further distinguished by the different correlations between profits and weights. In combination with three different numbers of items and three settings of the capacity, we have 27 instances in total, as shown in the column called “*Instance*”. Similarly to the settings in [11], every instance with “_01” postfix has a relatively small capacity. We expect such instances to be potentially easy to solve by DP and FPTAS due to the nature of the algorithms. The *OPT* column shows the optimum of each instance and the *RT(s)* columns illustrate the running time for each of the approaches in the time unit of a second. To demonstrate the quality of an approximate approach applied to the instances, we use the ratio between the objective value obtained by the algorithm and the optimum obtained for an instance as the approximation rate $AR(\%) = 100 \times \frac{OBJ}{OPT}$.

In the comparison of exact approaches, our results show that the DP is much quicker than the exact MIP and BIB in solving the majority of the instances. The exact MIP is slower than the DP in every case and this dominance is mostly significant. For example, it spends around 35 minutes to solve the instance *uncorr-s-w_10* with 1,000 items, where the DP needs around 15 seconds only. On the other hand, the BIB slightly beats the DP on three instances, but the DP is superior for the rest 24 instances. An extreme case is *b-s-corr_01* with 1,000 items where the BIB spends above 1.5 hours while the DP solves it in 11 seconds only. Concerning the running time of the DP, it significantly increases only for the instances having large amount of items with strongly correlated weights and profits, such as *b-s-corr_06* and *b-s-corr_10* with 1,000 items. However, *b-s-corr_01* seems exceptional due to the limited capacity assigned to the instance.

Our comparison between the approximation approaches shows that the FPTAS has significant advantages as well. The approximation ratios remain 100% when ϵ equals 0.0001 and 0.01. Only when ϵ is set to 0.25, the FPTAS starts to output the results having similar accuracies as the ones of *approxMIP*. With regard to the performance, the FPTAS takes less running time than *approxMIP* on the majority of the instances despite the setting of ϵ . As an extreme case, *approxMIP* requires hours to solve the *uncorr-s-w_01* instance with 1,000 items, but the FPTAS takes less than a second. However, the *approxMIP* performs much better on *b-s-corr_06* and *b-s-corr_10* with 1,000 items. This somehow indicates that the underlying factors that make instances hard to solve by approximate MIP and FPTAS have different nature. Understanding these factors more and using them wisely should help to build a more powerful algorithm with mixed features of MIP and FPTAS.

In our second experiment, we use test instances which are slightly different to those in the benchmark used in [11]. This is motivated by our findings that relaxing ϵ from

0.0001 to 0.75 improves the performance of FPTAS by around 50% for the b-s-corr instances, while does not degrade the accuracy noticeably. At the same time, there is no significant improvement for other instances. It's surprising as shows that the performance improvement can be easily achieved on complex instances. Therefore, we study how the FPTAS performs if the instances are more complicated. The idea is to use instances with large weights, which are known to be difficult regarding dynamic programming based approaches for the classical knapsack problem. We follow the same way to create TTP instances as proposed in [12] and generate the knapsack component of the problem as discussed in [9]. Specifically, we extend the range to generate potential profits and weights from $[1, 10^3]$ to $[1, 10^7]$ and focus on *uncorrelated* (uncorr), *uncorrelated with similar weights* (uncorr-s-w), and *multiple strongly correlated* (m-s-corr) types of instances. Additionally, in the stage of assigning the items of a knapsack instance to particular cities of a given TSP tour, we sort the items in descending order of their profits and the second city obtains k , $k \in \{1, 5, 10\}$, items of the largest profits, the third city then has the next k items, and so on. We expect that such assignment should force the algorithms to select items in the first cities of a route making the instances more challenging for the DP and FPTAS. In fact, these instances occur to be harder and force us to switch to the 128GB RAM and $8 \times (2.8\text{GHz AMD } 6 \text{ core processors})$ cluster machine to carry out the second experiment.

Table 2 illustrates the results of running the DP and FPTAS on the instances with the large range of profits and weights. Generally speaking, we can observe that the instances are significantly harder to solve than those ones from the first experiment, that is they take comparably more time. Similarly, the instances with large number of items, larger capacity, and strong correlation between profits and weights are now hard for the DP as well. Oppositely to the results of the previous experiment, the FPTAS performs much better when dealing with such instances in the case when ϵ is relaxed. For example, its performance is improved by 95% for the instance *m-s-corr_10* with 1,000 items when ϵ is raised from 0.0001 to 0.75 while the approximation rate remains at 100%.

Conclusion

Multi-component combinatorial optimisation problems play an important role in many real-world applications. We have examined the non-linear packing while traveling problem which results from the interactions in the TTP. We designed a dynamic programming algorithm that solves the problem in pseudo-polynomial time. Furthermore, we have shown that the original objective of the problem is hard to approximate and have given an FPTAS for optimising the amount that can be gained over the smallest possible travel cost. It should be noted that the FPTAS applies to a wider range of problems as our proof only assumed that the travel cost per unit distance in dependence of with weight w is monotone increasing and convex. Our experimental results on different types of knapsack instances show the advantage of the dynamic program over the previous approach based on mixed integer programming and branch-infer-and-bound concepts. Furthermore, we have demonstrated the effectiveness of the FPTAS on instances with a large weight and profit range.

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References

- [1] Bonyadi, M.; Michalewicz, Z.; and Barone, L. 2013. The travelling thief problem: The first step in the transition from theoretical problems to realistic problems. In *Evolutionary Computation (CEC), 2013 IEEE Congress on*, 1037–1044.
- [2] El Yafrani, M., and Ahiod, B. 2016. Population-based vs. single-solution heuristics for the travelling thief problem. In *Proceedings of the Genetic and Evolutionary Computation Conference 2016, GECCO '16*, 317–324. New York, NY, USA: ACM.
- [3] Faulkner, H.; Polyakovskiy, S.; Schultz, T.; and Wagner, M. 2015. Approximate approaches to the traveling thief problem. In *Proceedings of the 2015 Annual Conference on Genetic and Evolutionary Computation, GECCO '15*, 385–392. New York, NY, USA: ACM.
- [4] GOODYEAR. 2008. Factors Affecting Truck Fuel Economy. [http://www.goodyeartrucktires.com/pdf/resources/publications/Factors Affecting Truck Fuel Economy.pdf](http://www.goodyeartrucktires.com/pdf/resources/publications/Factors_Affecting_Truck_Fuel_Economy.pdf).
- [5] Hochbaum, D. 1997. *Approximation Algorithms for NP-hard Problems*. PWS Publishing Company.
- [6] Hoy, D., and Nikolova, E. 2015. Approximately optimal risk-averse routing policies via adaptive discretization. In Bonet, B., and Koenig, S., eds., *Proceedings of the Twenty-Ninth AAAI Conference on Artificial Intelligence, January 25-30, 2015, Austin, Texas, USA.*, 3533–3539. AAAI Press.
- [7] Lin, C.; Choy, K.; Ho, G.; Chung, S.; and Lam, H. 2014. Survey of green vehicle routing problem: Past and future trends. *Expert Systems with Applications* 41(4, Part 1):1118 – 1138.
- [8] Mei, Y.; Li, X.; and Yao, X. 2016. On investigation of interdependence between sub-problems of the travelling thief problem. *Soft Comput.* 20(1):157–172.
- [9] Pisinger, D. 2005. Where are the hard knapsack problems? *Computers & Operations Research* 32(9):2271 – 2284.
- [10] Polyakovskiy, S., and Neumann, F. 2015. Packing while traveling: Mixed integer programming for a class of nonlinear knapsack problems. In Michel, L., ed., *Integration of AI and OR Techniques in Constraint Programming*, volume 9075 of *Lecture Notes in Computer Science*. Springer International Publishing. 332–346.

- [11] Polyakovskiy, S., and Neumann, F. 2016. The packing while traveling problem. *European Journal of Operational Research* –. <http://dx.doi.org/10.1016/j.ejor.2016.09.035> (in press).
- [12] Polyakovskiy, S.; Bonyadi, M. R.; Wagner, M.; Michalewicz, Z.; and Neumann, F. 2014. A comprehensive benchmark set and heuristics for the traveling thief problem. In *Proceedings of the 2014 Annual Conference on Genetic and Evolutionary Computation, GECCO '14*, 477–484. New York, NY, USA: ACM.
- [13] Toth, P. 1980. Dynamic programming algorithms for the zero-one knapsack problem. *Computing* 25(1):29–45.
- [14] Yang, G., and Nikolova, E. 2016. Approximation algorithms for route planning with nonlinear objectives. In Schuurmans, D., and Wellman, M. P., eds., *Proceedings of the Thirtieth AAAI Conference on Artificial Intelligence, February 12-17, 2016, Phoenix, Arizona, USA.*, 3209–3217. AAAI Press.