A

Integer Programming

Here we collect some fundamental results of integer programming which are used throughout the text. We assume that the reader is familiar with linear programming, and recommend textbooks as [NW88, Wol98] for the theory of integer programming. All results of this short appendix can be found in both of these books.

We consider the following integer programming problem:

$$\textbf{(IP)} \quad \begin{array}{ll} \min & cx \\ \text{s.t.} & Ax \le b \\ & x \in \mathbb{Z}^n, \end{array}$$

where $c \in \mathbb{R}^n, b \in \mathbb{R}^m$ and A is an $m \times n$ matrix.

Definition A.1. *The* **linear programming relaxation (LP-IP)** *or short* **LP-relaxation** *of an integer program (IP) is given by deleting the integer constraints, i.e.*

$$\begin{array}{ll} \textbf{(IP)} & \min\{cx \ s.t. \ Ax \le b, x \in \mathbb{Z}^n\} \\ \textbf{(LP-IP)} & \min\{cx \ s.t. \ Ax \le b, x \in \mathbb{R}^n\}. \end{array}$$

The relation between an integer program (IP) and its LP-relaxation (LP-IP) is the following.

Lemma A.2. *Let*

$$\begin{array}{l} z^* = cx^* = \min\{cx \ s.t. \ Ax \le b, x \in \mathbb{Z}^n\} \\ \bar{z} = c\bar{x} = \min\{cx \ s.t. \ Ax \le b, x \in \mathbb{R}^n\}. \end{array}$$

Then

(i) $\bar{z} \le z^*$

(ii) If $\bar{x} \in \mathbb{Z}^n$ *then* $z^* = \bar{z}$ *and* $x^* = \bar{x}$ *is an optimal solution of (IP).*

The lemma states that each solution of the LP-relaxation gives a lower bound on the original program. Moreover, if the solution of the LP-relaxation happens to be integer, it is the optimal solution of the integer program. This observation can be used to find polynomially solvable special cases of integer programs, namely, if all vertices of the feasible set $\{x : Ax \leq b, x \in \mathbb{R}^n\}$ of (LP-IP) are integer. In this case, we know that all basic solutions are integer, and hence we conclude from the theory of linear programming that there exists an *integer* optimal solution $\bar{x}$. Lemma A.2 then yields the optimality of $\bar{x}$ for the original integer program. Thus, in that case it is enough to solve the LP-relaxation of the integer program.

To identify integer programs in which all vertices of the feasible set are integer, we need the concept of *total unimodularity*.

Definition A.3. *A matrix A is* **totally unimodular**, *if $det(B) \in \{-1, 0, 1\}$ for all square submatrices B of A.*

If A is a totally unimodular matrix, then

- $a_{ij} \in \{-1, 0, 1\}$ for all entries of the matrix A,
- the transposed A^T is totally unimodular,
- $(A|I)$ is totally unimodular (I is the $m \times m$ unit matrix).

An example of a matrix with entries only in $\{-1, 0, 1\}$, but that is not totally unimodular, is the following:

$$\begin{pmatrix} 1 & 0 & -1 \\ 0 & -1 & 0 \\ 1 & 1 & 1 \end{pmatrix}.$$

Totally unimodular matrices are important since their corresponding integer programs can be solved by linear programming methods.

Theorem A.4. *Let $b \in \mathbb{Z}^m$ and let A be totally unimodular. Then all vertices of $\{x \in \mathbb{R}^n : Ax \leq b\}$ are integer. Consequently, each optimal basic solution of (LP-IP) is an optimal solution for (IP).*

Examples of totally unimodular matrices (resulting in polynomially solvable integer programs) are

- incidence matrices of networks; this result is used in Sections 7.1 and 8.4 in Part II,
- matrices with the consecutive ones property, which play an important role in Sections 3.4, 3.6, and in 4.3 in Part I,
- network matrices, mentioned both in Section 3.4 (Part I) and in Section 7.3 (Part II).

B

Bicriteria Optimization

Here we briefly introduce bicriteria optimization problems, which are discussed in Chapters 4 and 9. For an introduction to multicriteria optimization we refer the reader to textbooks (e.g. [Ehr00]), a detailed state-of-the art survey of the field is given by [FGE05]. The results of this short overview can be found e.g. in [Ehr00].

All bicriteria problems treated in this text are combinatorial optimization problems, such that we will assume that the feasible set Feas consists of a discrete set of points, i.e.,

$$\text{Feas} \in \mathbb{Z}^n.$$

The bicriteria optimization problem we consider is given by a feasible set $\text{Feas} \subseteq \mathbb{Z}^n$ and two objective functions $f_1, f_2 : \text{Feas} \to \mathbb{R}$.

$$\textbf{(BP)} \quad \min_{x \in \text{Feas}} \begin{pmatrix} f_1(x) \\ f_2(x) \end{pmatrix}.$$

Definition B.1. *Let* $x_1, x_2 \in \text{Feas}$.

- x_1 **dominates** x_2 *if*

$$f_1(x_1) \leq f_1(x_2) \text{ and}$$
$$f_1(x_1) \leq f_1(x_2),$$

  where at least one of the inequalities is strict.
- $x \in \text{Feas}$ *is a* **Pareto solution**, *if there does not exist any* $y \in \text{Feas}$ *that dominates* x.

The goal in bicriteria optimization is to determine the Pareto solutions, i.e., the set of all $x \in \text{Feas}$ which are non-dominated. However, it often is enough to know the objective values of the Pareto solutions. To this end, let

$$f(\text{Feas}) = \left\{ \begin{pmatrix} f_1(x) \\ f_2(x) \end{pmatrix} : x \in \text{Feas} \right\}$$

denote the objective space of (BP). Then a point $\begin{pmatrix} f_1(x) \\ f_2(x) \end{pmatrix} \in f(\text{Feas})$ is called *efficient*, if $x \in$ Feas is a Pareto solution.

For an illustration, see Figure B.1. In this example let us assume that the set of objective values for all points $x \in$ Feas is given by the points depicted in the figure. Then the five filled points $p_1, \ldots, p_5$ are not dominated by any other point, i.e., exactly these points are efficient.

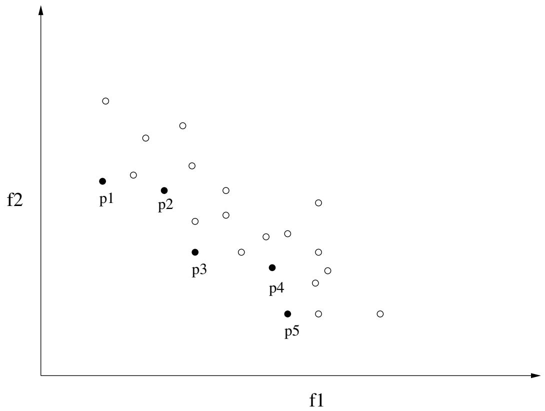

Fig. B.1. Efficient solutions of a bicriteria optimization problem.

For finding Pareto solutions we can solve a one-criteria optimization problem. This method is called *weighted sum scalarization*.

Theorem B.2. *If x is an optimal solution of*

$$\mathbf{BP}(\lambda) \qquad \min_{x \in \text{Feas}} \lambda f_1(x) + (1-\lambda) f_2(x)$$

for some $0 < \lambda < 1$, then x is a Pareto solution of (BP).

Unfortunately, not all Pareto solutions can be found by weighted sum scalarization, if the set Feas $\subseteq \mathbb{Z}^n$ consists of a discrete set of points. In Figure B.1, the efficient points p_1, p_3, and p_5 can be found by solving a weighted sum problem, while no λ exists such that p_2 and p_4 are optimal solutions of BP(λ).

Definition B.3. *A Pareto solution x is called* **supported** *if there exists λ with $0 < \lambda < 1$ such that x is the optimal solution of BP(λ).*

Note that the term *supported* is due to the following fact: If x is a supported Pareto solution, then $f(x) = \begin{pmatrix} f_1(x) \\ f_2(x) \end{pmatrix}$ lies on the boundary of the convex hull of $f(\text{Feas})$. Hence there exists a supporting line of $f(\text{Feas})$ passing through $f(x)$.

By weighted sum scalarization, we find exactly the set of supported Pareto solutions. With the following result we can also find non-supported Pareto solutions. It uses the constraint versions of (BP).

Lemma B.4. *Let $\{i,j\} = \{1,2\}$ and let x be a unique optimal solution of*

$$\min\{f_i(x) : x \in \text{Feas} \quad \textit{and} \quad f_j(x) \le y_j\}.$$

Then x is a Pareto solution of (BP).

Finally, we state the definition of lexicographic minimal solutions.

Definition B.5. *Let $\{i,j\} = \{1,2\}$. x is called a* **lexicographic minimal** *solution of (BP) for the order (f_i, f_j) if for all $y \in \text{Feas}$ one of the following conditions holds.*

- *Either $f_i(x) < f_i(y)$,*
- *or $f_i(x) = f_i(y)$ and $f_j(x) \le f_j(y)$.*

Note that the lexicographic minimal solutions are always Pareto solutions.

C

Gauges as Distance Measures

In the stop location problem (Part I) it is important to choose a suitable function to measure the distance from a demand point to a stop or station. Hence, in this section we briefly introduce the concept of gauges. For more information, the reader is referred to [Min67], which is also the basis of this appendix. Note that gauges have been used frequently in location theory, see, e.g., [DKSW01]. Although the following definitions and results can directly be transferred to $\mathbb{R}^n$ we only present the notation for two dimensions, since we obviously only deal with stop location in the plane.

Geometrical observations play an important role for defining the candidate set in Part I. Thus, it makes sense to use the following "geometrical" definition of a norm.

Definition C.1. *Let B be a compact convex set in $\mathbb{R}^2$ with nonempty interior which is symmetric with respect to the origin. Let $x \in \mathbb{R}^2$. Then define the* **norm** $\gamma : \mathbb{R}^2 \to \mathbb{R}$ *as*

$$\gamma(x) := \inf\{\lambda > 0 : x \in \lambda B\}.$$

The following Lemma C.2 states that γ satisfies the properties required for norms, i.e., for all $x, y \in \mathbb{R}^2$ and $\lambda \in \mathbb{R}$ we have

$$\gamma(x) \geq 0 \tag{C.1}$$

$$\gamma(x) = 0 \Longleftrightarrow x = 0 \tag{C.2}$$

$$\gamma(\lambda x) = |\lambda|\gamma(x) \text{ and} \tag{C.3}$$

$$\gamma(x + y) \leq \gamma(x) + \gamma(y). \tag{C.4}$$

On the other hand, all norms can be characterized by their **unit balls** B.

Lemma C.2. *The following results hold.*

1. *Let γ be given as in Definition C.1. Then γ satisfies (C.1) – (C.4).*
2. *Let $\gamma : \mathbb{R}^2 \to \mathbb{R}_{\geq 0}$ be given, such that γ satisfies (C.1) – (C.4). Then its unit ball $B_\gamma = \{x \in \mathbb{R}^2 : \gamma(x) \leq 1\}$ is a compact convex set with nonempty interior which is symmetric with respect to the origin.*

Examples for norms are

- the Euclidean norm $l_2(x) = \sqrt{(x_1)^2 + (x_2)^2}$,
- the Manhattan norm $l_1(x) = |x_1| + |x_2|$,
- the maximum norm (or Chebyshev norm) $l_\infty(x) = \max\{|x_1|, |x_2|\}$,
- the p-norms $(1 \leq p < \infty)$ $l_p(x) = \sqrt[p]{|x_1|^p + |x_2|^p}$.

The corresponding unit balls for the first three examples are depicted in Figure C.1.

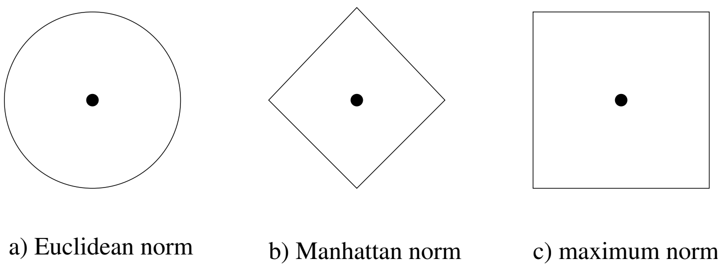

Fig. C.1. The unit balls of the Euclidean, the Manhattan and the maximum norm.

If we drop the assumption that the set B is symmetric in Definition C.1, then B does not define a norm, but a *gauge*.

Definition C.3. *Let B be a compact convex set in $\mathbb{R}^2$ containing the origin in its interior. The* **gauge** *of x with respect to B is then defined as*

$$\gamma(x) := \inf\{\lambda > 0 : x \in \lambda B\}.$$

Note that the convexity of B is still required, but $\gamma(-x) = \gamma(x)$ does not hold in general without the symmetry assumption.

The distance between two points $x, y \in \mathbb{R}^2$ is defined by

$$d(x, y) = \gamma(y - x).$$

If γ is a norm we obtain $d(x, y) = d(y, x)$, while this need not be the case for a gauge γ.

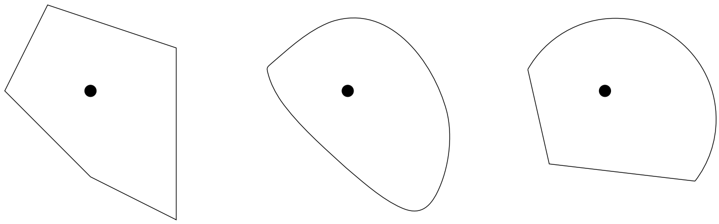

Fig. C.2. Examples of gauges that are not norms.

Examples of gauges which are not norms are given in Figure C.2. In public transportation, a distance measure for some demand point d can be constructed by defining

$$B_d = \{x \in \mathbb{R}^2 : x \text{ can be reached within a time of } r \text{ minutes}\}$$

as the unit ball for demand point d and using the corresponding gauge γ_{B_d} as the required distance measure. Note that the shape of B_d depends on the road network structure and on the public transportation system in the area around d.

4

Frequently Used Notation

General notation:

$\mathbb{N}$	natural numbers including 0
$\mathbb{Z}$	integer numbers
$\mathbb{R}$	real numbers
$\{u, v\}$	undirected edge in a graph
(u, v)	directed edge in a digraph
A^T	transpose of a matrix
Θ	node-arc incidence matrix of a network

Public transportation network:

$\mathrm{PTN} = (V, E)$	public transportation network
V	set of stops of the PTN elements denoted by u, v, v_i
E	set of direct rides in the PTN elements denoted by $\{u, v\}$, or by e

Data about customers:

$W = (W_{uv})$	OD-matrix, i.e., number of customers traveling from u to v
c_e	traffic load on edge $e \in E$, i.e., number of customers traveling along edge e
c_v	traffic load through stop $v \in V$ i.e., number of customers traveling through stop v

w_d	demand in demand point $d \in \mathcal{D}$
w_D	demand in demand region $D \in \mathcal{D}$
w_p	number of customers traveling along path $p \in \mathcal{P}$
w_a	"traffic load" on activity $a \in \mathcal{A}$
w_i	number of customers really getting off at event $i \in \mathcal{E}$

Stop location:

$\mathcal{D}$	set of demand points or demand regions
	elements denoted by d for demand points and by D for demand regions
$G = (V, E)$	given graph in which the stops are to be located
$\mathcal{T}$	tracks, given as points on the embedding of graph G
γ_d	gauge distance function of demand point $d \in \mathcal{D}$
γ_D	gauge distance function of demand region $D \in \mathcal{D}$
$g(s)$	edge e or node v in which point $s \in \mathcal{T}$ is located
S^{ex}	existing stops or stations
S	set of new stops or stations

Delay management:
(in the notation using event-activity networks)

$\mathcal{P}$	set of paths of customers
$\mathcal{N} = (\mathcal{E}, \mathcal{A})$	event-activity network
$\mathcal{E}_{arr}$	arrival events
$\mathcal{E}_{dep}$	departure events
$\mathcal{A}_{wait}$	waiting activities
$\mathcal{A}_{drive}$	driving activities
$\mathcal{A}_{change}$	changing activities
Π_i	time for event $i \in \mathcal{E}$ in the original timetable
x_i	time for event $i \in \mathcal{E}$ in the perturbed timetable
y_i	delay of event $i \in \mathcal{E}$
s_a	slack time of activity $a \in \mathcal{A}$
d_i	source delay of event $i \in \mathcal{E}$
$\mathcal{E}_{del}$	set of delayed events

Tariff planning:

$\mathcal{Z}$	zone partition
$c(p)$	price for traveling through $p + 1$ zones, i.e., for passing p zone borders
L	required number of zones
n_{uv}	number of zones needed for traveling from u to v
d_{uv}	reference price for a ticket from u to v
M_p	set of relations passing p zones

5

List of the Main Problems

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