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Abstract

The lane covering game (LCG) is a cooperative game where players cooperate to reduce the cost of cycles that cover their required lanes on a network. We discuss the possibilities/impossibilities of a complete characterization of the core via dual solutions in LCGs played among a collection of shippers, each with a number of service requirements along some lanes, and show that such a complete characterization is possible if each shipper has at most one service requirement.

1 Introduction

In any cooperative situation, the division of joint costs is a critical issue. The *core* of a cooperative game contains allocations that provide players with sufficient incentives to remain in the grand coalition. In general, finding an allocation in the core as well as testing the core-membership of a given allocation are computationally difficult problems as they involve dealing with a number of inequalities which grow exponentially in the number of players. In linear production games (Owen, 1975), every solution to the corresponding dual linear program yields an allocation in the core thus core allocations can be found in polynomial time (Schrijver, 1998). Although testing the membership of a given allocation to the core for this class of games is generally co-NP-complete (Fang et al., 2002), in some cases, e.g. flow games on simple networks (Kalai and Zemel, 1982), dual solutions obtain *all* allocations in the core. This note addresses the possibilities/impossibilities of a complete characterization of the core via dual solutions in *lane covering games*.

The lane covering game (LCG), introduced by Özener and Ergun (2008), can be represented as an instance of linear production games where players cooperate to reduce the cost of cycles that cover their required lanes. Özener and Ergun (2008) show that if each required lane is considered to be a single player, the dual solutions completely characterize the core of corresponding game. We extend and complete this result by allowing *shippers* to be the actual players. Each shipper might have several service requirements (across one or multiple lanes). We specify the situations in which the core can or cannot be completely characterized by dual solutions. The main contribution of this note is to prove that a complete characterization of the core via duals is possible if every shipper has at most one service requirement. We also provide examples of LCGs where such a complete characterization fails.

2 Lane Covering Games (LCG)

Consider a collection of locations and the network of roads in between. There are several shippers who provide truckload deliveries between pairs of locations. After fulfilling its planned deliveries, every shipper must return to its starting location (repositioning). By collaboration, shippers can reduce the total repositioning cost needed for fulfilling their consolidated deliveries.

Consider the complete directed graph $G = (N, A)$ where N is a finite set of nodes and $A = \{ij | i, j \in N, i \neq j\}$ is the set of ordered lanes. The service cost vector $c = (c_{ij})_{ij \in A}$ gives the non-negative costs of servicing the lanes. Traversing lane ij without providing service would cost θc_{ij} with $0 \leq \theta \leq 1$. A finite set of shippers (players) P operate on G. A given player $k \in P$ has an individual *requirement vector* $r^k = (r^k_{ij})_{ij \in A}$ where $r^k_{ij} \in \mathbb{N} \cup \{0\}$ is the number of service requirements of k along the lane ij. A player k is called a *simple shipper* if $\sum_{ij \in A} r^k_{ij} = 1$. That is, a simple shipper has a single service requirement. We define a *lane covering situation* as the tuple $\Gamma = (G, c, \theta, P, (r^k)_{k \in P})$.

A cooperative cost game is a pair (P, z) with the set of players P and $z : 2^P \to \mathbb{R}$ being the characteristic function that assigns to every coalition $S \subseteq P$ the cost $z(S)$. The *lane covering game* (LCG) associated with situation Γ is a cooperative cost game (P, z^Γ) where $z^\Gamma(S)$ is the minimum cost of covering the service requirements of $S \subseteq P$, i.e. $r^S = \sum_{k \in S} r^k$, via cycles. For any $S \subseteq P$, $z^\Gamma(S)$ can be obtained by the following integer linear program:

$$\textbf{Model 1:} \qquad z^\Gamma(S) = \min \sum_{ij \in A} c_{ij} x_{ij} + \theta c_{ij} w_{ij} \tag{1}$$

$$\text{s.t.} \sum_{j \in N \setminus \{i\}} x_{ij} - x_{ji} + w_{ij} - w_{ji} = 0 \qquad \forall i \in N \tag{2}$$

$$x_{ij} \geq r^S_{ij} \qquad \forall ij \in A \tag{3}$$

$$x_{ij}, w_{ij} \in \mathbb{N} \cup \{0\} \qquad \forall ij \in A \tag{4}$$

where x_{ij} and w_{ij} denote the number of times lane ij is traversed with and without service respectively. We denote an optimal solution for the above problem with $(x^S_{ij}; w^S_{ij})_{ij \in A}$. Model 1 corresponds to a minimum-cost circulation problem with its constraints forming a totally unimodular matrix (Schrijver, 1998). Thus with integer requirement vectors, the linear relaxation of Model 1 does not affect the optimal solution.

The dual associated with the linear relaxation of Model 1 for P is

$$\textbf{Model 2:} \qquad d^\Gamma = \max \sum_{ij \in L} r_{ij}^P I_{ij} \tag{5}$$

$$\text{s.t. } I_{ij} + y_i - y_j \le c_{ij} \qquad \forall ij \in A \tag{6}$$

$$y_i - y_j \le \theta c_{ij} \qquad \forall ij \in A \tag{7}$$

$$I_{ij} \ge 0 \qquad \forall ij \in A \tag{8}$$

where $L = \{ij | r_{ij} > 0\}$ is the *set of required lanes*. Let $I^\Gamma = (I_{ij}^\Gamma)_{ij \in A}$ be an optimal solution for d^Γ. For a required lane $ij \in L$, I_{ij}^Γ gives the shadow price that determines the amount of decrease in $z^\Gamma(P)$ resulting from reducing r_{ij}^P by one. We denote the set of all solutions to d^Γ with $\boldsymbol{I}^\Gamma$.

3 Core and Dual Allocations

Given P, an allocation $\beta = (\beta^k)_{k \in P}$ is a vector containing a real number for every player in P. The allocation β is in the core of the game (P, z) if and only if it is efficient, i.e. $\sum_{k \in P} \beta^k = z(P)$, and stable, i.e. $\sum_{k \in S} \beta^k \le z(S)$ for all $S \subset P$.

Owen (1975) introduces the class of *linear production games* and shows that an allocation in the core of these games can be obtained from a solution to the dual problem. As discussed in Özener and Ergun (2008), the game (P, z^Γ) with $z^\Gamma(S)$ defined by the LP-relaxation of Model 1 for every $S \subseteq P$ is an instance of the class of linear production games. Thus, an allocation in the core of (P, z^Γ) can be obtained from a dual solution in the following manner:

$$\beta^k = \sum_{ij \in L} r_{ij}^k I_{ij}^\Gamma, \qquad \forall k \in P. \tag{9}$$

Thus, in LCGs every dual solution obtains an allocation in the core. The question concerning a complete characterization of core via dual solutions addresses the reverse of the latter, i.e. does every core allocation correspond to a dual solution?

4 LCGs with General Shippers

In this section we show that a complete characterization of the core via duals is not possible if some players have multiple service requirements (general shippers). The following example shows that this is the case even if every lane requires service at most once.

Example 1. *Consider the lane covering situation associated with the graph in Figure 1. The service costs across lanes with opposite directions are symmetric and are given in the figure. We let* $\theta = 1$. *Consider two players* $P = \{A, B\}$ *with player A requiring service on lanes* 12 *and* 13, *and player B requiring service along the lane* 41. *We have* $z^\Gamma(\{A\}) = z^\Gamma(\{B\}) = 8$, *and* $z^\Gamma(P) = 13$. *Observe that the core of* (P, z^Γ) *is completely characterized by the allocations* $\beta = (\beta^A, \beta^B) = (8 - \epsilon, 5 + \epsilon)$ *with* $0 \le \epsilon \le 3$. *In every dual solution for this situation it holds that* $I_{12}^\Gamma = 4$, $I_{13}^\Gamma = 4$, $I_{41}^\Gamma = 5$. *Thus, the allocation obtained from the dual solutions is unique and equivalent to* $\beta^A = 8$ *and* $\beta^B = 5$. △

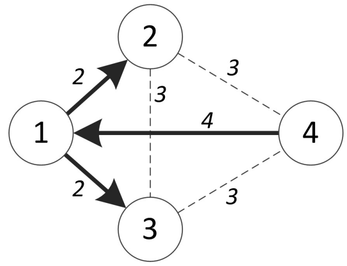

Figure 1: The network in Example 1

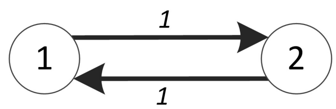

Figure 2: The network in Example 2

The next example illustrates that with general shippers a complete characterisation of the core via duals also fails even if the requirements of all shippers are separated on lanes such that no shipper requires service along more than one lane.

Example 2. *Consider the lane covering situation associated with the graph in Figure 2 and three players $P = \{A, B, C\}$ where both players A and B require a single service along the lane 12 and player C requires service along the lane 21 twice. Let $c_{12} = c_{21} = \theta = 1$. We have $z^{\Gamma}(S) = 2$ if $S \in \{\{A\}, \{B\}\}$ and $z^{\Gamma}(S) = 4$ for all other $S \subseteq N$, $S \neq \emptyset$. It is straightforward to check that the allocation $\beta = (\beta^A, \beta^B, \beta^C) = (1.5, 0.5, 2)$ belongs to the core. However, in every allocation obtained via duals from (9) it holds that $\beta^A = \beta^B = I^{\Gamma}_{12}$.* $\triangle$

The above example demonstrates that in LCGs, core allocations might give unequal costs to shippers who require service on the same lane. These allocations are unobtainable via dual solutions.

5 LCGs with Simple Shippers

In the rest of this section we assume that Γ is a lane covering situation where all players are simple shippers. We show that in these situations dual solutions completely characterize the core. For this purpose, we introduce additional notation.

Given a situation Γ, an optimal solution $(x^S_{ij}; w^S_{ij})_{ij \in A}$ to Model 1 for $S \subseteq P$ induces a directed multigraph $\mathcal{G}(S) = (N, \mathcal{A}(S))$ where for any $ij \in A$, the $\mathcal{A}(S)$ contains x^S_{ij} number of lanes with cost c_{ij}, i.e. type x (service) lanes, and w^S_{ij} number of lanes with cost θc_{ij}, i.e. type w (repositioning) lanes, from i to j. Without loss of generality, hereafter we consider optimal solutions where $x^S_{ij} = r^S_{ij}$ for all $ij \in A$. A *simple cycle* on $\mathcal{G}(S)$ is defined as a sequence of nodes $n_0, ..., n_t$ and lanes, such that all nodes are non-identical except for $n_0 = n_t$ and there exists exactly one lane (of either type x or w) between any consecutive pair of nodes. Constraint (2) in Model 1 ensures that for every node $i \in N$ the number of lanes in $\mathcal{A}(S)$

whose end nodes are i is equal to the number of lanes whose start nodes are i. Therefore, by Veblen's theorem (Bondy and Murty, 2008), the $\mathcal{A}(S)$ can be decomposed into a set of simple cycles. Let $\mathscr{C}^S$ be such a decomposition. We refer to $\mathscr{C}^S$ as a decomposition of an optimal service plan for coalition S into simple cycles. We denote a simple cycle in $\mathscr{C}^S$ by $C = (C^x; C^w)$ where $C^x = (C^x_{ij})_{ij\in A}$ and $C^w = (C^w_{ij})_{ij\in A}$ are vectors containing type x and type w lanes of C respectively. Note that by definition of simple cycles we have $C^x_{ij}, C^w_{ij} \in \{0,1\}$ for all $ij \in A$. The cost of a simple cycle $C \in \mathscr{C}^S$ is $\lambda_C = \sum_{ij\in A} c_{ij}C^x_{ij} + \theta c_{ij}C^w_{ij}$. Accordingly, we have $z^\Gamma(S) = \sum_{C\in\mathscr{C}^S} \lambda_C$.

Given $C \in \mathscr{C}^P$, we define $S_C = \{S \subseteq P | \sum_{k\in S} r^k = C^x\}$ as a set of serviced shippers in C. Note that S_C is not necessarily unique. The following lemma states that the cost of a simple cycle $C \in \mathscr{C}^P$ equals the cost of the coalition of a set of serviced shippers in C.

Lemma 1. *Let $\mathscr{C}^P$ be a decomposition of an optimal service plan for coalition P into simple cycles. For all $C \in \mathscr{C}^P$ and any S_C we have $\lambda_C = z^\Gamma(S_C)$.*

Proof. Clearly $\lambda_C \geq z^\Gamma(S_C)$ since any set of serviced shippers in C, i.e. S_C, can together use C for covering their required lanes. On the other hand, $\lambda_C > z^\Gamma(S_C)$ implies that $\mathscr{C}^P \ni C$ does not correspond to an optimal solution as in this case replacing C with $\mathscr{C}^{S_C}$ would result in a lower total cost. Therefore $\lambda_C = z^\Gamma(S_C)$. □

Next, we show that any allocation in the core divides the entire cost of a simple cycle $C \in \mathscr{C}^P$ among a set of serviced shippers in C.

Lemma 2. *Let $(\beta^k)_{k\in P}$ be an allocation in the core of (P, z^Γ) and $\mathscr{C}^P$ be a decomposition of an optimal service plan for coalition P into simple cycles. For all $C \in \mathscr{C}^P$ and any S_C we have $\sum_{k\in S_C} \beta^k = z^\Gamma(S_C)$.*

Proof. By Lemma 1, it suffices to show that $\sum_{k\in S_C} \beta^k = \lambda_C$. Since $(\beta^k)_{k\in P}$ is a core allocation, it holds that $\sum_{k\in S_C} \beta^k \leq \lambda_C$. Fix a S_C and consider the rest of the players, $P \setminus S_C$. A core allocation satisfies $\sum_{k\in P\setminus S_C} \beta^k \leq \sum_{C'\in\mathscr{C}^P\setminus C} \lambda_{C'}$. We have

$$\sum_{k\in S_C} \beta^k = \sum_{k\in P} \beta^k - \sum_{k\in P\setminus S_C} \beta^k \geq \sum_{C'\in\mathscr{C}^P} \lambda_{C'} - \sum_{C'\in\mathscr{C}^P\setminus C} \lambda_{C'} = \lambda_C$$

Therefore, it must be the case that $\sum_{k\in S_C} \beta^k = \lambda_C$. □

We are now ready to show that any allocation in core gives equal costs to players requiring the same lane.

Theorem 1. *Let $l, l' \in P$ be such that $r^l = r^{l'}$. Let $(\beta^k)_{k\in P}$ be an allocation in the core of (P, z^Γ). We have $\beta^l = \beta^{l'}$.*

Proof. Let $\mathscr{C}^P$ be a decomposition of an optimal service plan for coalition P into simple cycles. Consider $C \in \mathscr{C}^P$ and S_C such that $l \in S_C$. Since $r^l = r^{l'}$, by definition of S_C it holds that $\sum_{k\in S_C} r^k - r^l + r^{l'} = C^x$. Thus, $S'_C = S_C \setminus \{l\} \cup \{l'\}$ also corresponds to a set of serviced shippers in C. By Lemma 2, we have $\sum_{k\in S_C} \beta^k = \sum_{k\in S'_C} \beta^k = \lambda_C$ which obtains $\beta^l = \beta^{l'}$. □

Before presenting the main result of this section, we highlight the following property of LCGs.

Lemma 3. *Let $\beta = (\beta^k)_{k \in P}$ be an allocation in the core of a LCG with simple shippers only. We have $\beta^k \geq 0$ for all $k \in P$.*

Proof. Suppose β is an allocation in the core such that for player $l \in P$ it holds that $\beta^l < 0$. By efficiency it must be that $\sum_{k \in P \setminus \{l\}} \beta^k > z^\Gamma(P)$. Since β is in the core, we have $\sum_{k \in P \setminus \{l\}} \beta^k \leq z^\Gamma(P \setminus \{l\})$. Therefore it must hold that $z^\Gamma(P) < z^\Gamma(P \setminus \{l\})$. As every optimal solution to $z^\Gamma(P)$ is a feasible solution to $z^\Gamma(P \setminus \{l\})$, the latter inequality is impossible for any LCG. Therefore, we must have $\beta^l \geq 0$ and consequently $\beta^k \geq 0$ for all $k \in P$. □

We are now ready to provide the main result of this section.

Theorem 2. *Let Γ be a lane covering situation. If all players in Γ are simple, then the core of (P, z^Γ) is completely characterized by the set of corresponding dual solutions.*

Proof. Let $I = (I_{ij})_{ij \in A}$ be a vector of variables defined over the lanes in A. It directly follows from Theorem 1 and Lemma 3 that with simple shippers only, all allocations in the core are of the form $\beta = (\sum_{ij \in A} r^k_{ij} I_{ij})_{k \in P}$ for some $I = (I_{ij})_{ij \in A}$ with $I_{ij} \geq 0$ for all $ij \in A$. Hence, it suffices to show that if β is in the core, then $I \in \boldsymbol{I}^\Gamma$. We first show that if β is in the core, then the following program is feasible:

$$\textbf{Model 3:} \qquad \min \sum_{ij \in A} (c_{ij} - I_{ij}) x_{ij} + \theta c_{ij} w_{ij} \tag{10}$$

$$\text{s.t.} \sum_{j \in N \setminus \{i\}} x_{ij} - x_{ji} + w_{ij} - w_{ji} = 0 \qquad \forall i \in N \tag{11}$$

$$x_{ij}, w_{ij} \geq 0 \qquad \forall ij \in A \tag{12}$$

Since $(x^P_{ij}; w^P_{ij})_{ij \in A}$ is a feasible solution to Model 3, we need to show that the latter program is not unbounded. Note that Model 3 corresponds to a minimum-cost circulation problem on a network with reduced service costs wherein all type x lanes from i to j have the cost $c_{ij} - I_{ij}$ and all type w lanes from i to j have the cost θc_{ij}. The cost of a simple cycle C on this network is $\tilde{\lambda}_C = \sum_{ij \in A} (c_{ij} - I_{ij}) C^x_{ij} + \theta c_{ij} C^w_{ij}$. Suppose that the program is unbounded. If this is the case, then a cycle could be constructed on this network such that $\tilde{\lambda}_C < 0$. The latter implies that $\lambda_C < \sum_{ij \in A} I_{ij} C^x_{ij}$. Since $z^\Gamma(S_C) \leq \lambda_C$ it must be that $z^\Gamma(S_C) < \sum_{ij \in A} I_{ij} C^x_{ij} = \sum_{k \in S_C} \sum_{ij \in A} r^k_{ij} I_{ij} = \sum_{k \in S_C} \beta^k$ which is possible only if β is not stable, a contradiction. We conclude that if β is in the core, then the program in Model 3 is feasible. Next, observe that the dual solution to Model 3 is characterized by the following constraints:

$$y_i - y_j \leq c_{ij} - I_{ij} \qquad \forall ij \in A \tag{13}$$

$$y_i - y_j \leq \theta c_{ij} \qquad \forall ij \in A \tag{14}$$

From the first step it follows that if β is a stable allocation, then the program in Model 3 is feasible which indicates that a vector $y = (y_i)_{i \in N}$ can be found such that constraints in (13) and (14) are satisfied. This in conjunction with the fact that $I_{ij} \geq 0$ for all $ij \in A$ and considering that $\sum_{k \in P} \sum_{ij \in A} r^k_{ij} I_{ij} = \sum_{ij \in A} r^P I_{ij} = z^\Gamma(P)$ yield that $I \in \boldsymbol{I}^\Gamma$. □

	Every lane is required by at most one shipper	*Some lanes are required by multiple shippers*
Every shipper requires at most one lane	**Possible** (Theorem 2)	**Possible** (Theorem 2)
Some shippers require multiple lanes	**Impossible** (Example 1)	**Impossible** (Example 2)

Table 1: Possibility of a complete characterization of the core via duals in LCG

6 Concluding Remarks

In this note we extended the analysis of LCGs with respect to the possibilities of a complete characterization of the core via dual solutions. Instead of considering lanes as surrogate players, which is the case in Özener and Ergun (2008), we allowed shippers to be the players. Accordingly, we delineated the situations wherein a complete characterization of the core via duals are possible. An overview of the results are given in Table 1. As we proved, such a characterization is possible if each shipper has at most one service requirement. In this case, the dual solutions could completely characterize the core even if multiple shippers require service along the same lane. However, multiplicity of shippers' service requirement hinder such a complete characterization, even if multiple service requirements of each shipper is along a single lane. In conclusion, our analysis shows that focusing solely on the allocations obtained via dual solutions could significantly limit the number of options for choosing "fair" allocations in LCGs.

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