Job Security, Stability and Production Efficiency^{*}

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Abstract

We study a 2-sided labor market with a set of heterogeneous firms and workers in an environment where jobs are secured by regulation. Without job security Kelso and Crawford have shown that stable outcomes and efficiency prevail when all workers are (weak) gross substitutes to each firm, in the sense that increases in other workers' salaries can never cause a firm to withdraw an offer from a worker whose salary has not risen. It turns out that by introducing job security, stability and efficiency may still prevail, and even for a significantly broader class of production functions.

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1 Introduction

Since the work of Kelso and Crawford (1982) the 2-sided many-to-many matching model has emerged as the prominent tool to analyze labor markets whenever firms and workers are heterogeneous. The assumption underlying many results in this literature is that firms' preferences over sets of workers exhibit "gross-substitutability". The Kelso and Crawford model assumes that workers and firms negotiate over a single parameter, the worker's salary, and the particular details of the job are given (such as working hours, shifts, vacation days, insurance). Hatfield and Milgrom (2005) generalize this matching-based model to a 'contracts model' where a multi-dimensional set of feasible contracts between firms and workers exists. In such a model the productivity of a set of workers is not just based on their identity as in Kelso and Crawford but also on the nature of the contract. Hatfield and Milgrom go on and show that in this more general model gross-substitutability (suitably defined) drives many similar results (such as existence of non-empty core and efficiency). Echenique (2012) shows that under this assumption both models are equivalent.¹

The notion of stability, initially due to Gale and Shapley (1962), is the standard solution concept for matching models in general and for labor markets in particular. A stable outcome is an allocation of workers to firms (of which one firm is the outside option of unemployment) and a salary vector for the workers such that no combination of a single firm and a set of workers can improve their position while disregarding the others (there is no 'blocking coalition'). Underlying the logic of this solution concept is the notion of a free, unregulated, competitive market, where any coalition can withdraw from the market if the market does not provide them with a desired outcome.

However, many existing labor markets are regulated and allow various degrees of job security. In most European countries many employees have indefinite contracts which make it very difficult and very costly for an employer to terminate a contract. In the UK, for example, the tenure necessary to qualify for such protection was lowered in 1999 from 24 to 12 months (Marinescu, 2009). In Germany, the 1951 Dismisal Protection Act which is still largely valid today acknowledges that workers have the right to keep their jobs, and, for example, fixed term contracts are allowed only for a period of up to 18 months (Emmenegger and Marx, 2011). High job security exists in many non-European countries as well. In India,

¹Recent work by Hatfield and Kojima (2010) demonstrate the limitation of the Echenique critique regarding Hatfield and Milgrom's 'contracts model' and shows that when considering larger classes of production functions the two models diverge. Sönmez and Switzer (2013) leverage these observations to solve the problem of cadet assignment in the US army where the standard substitutability assumption does not hold.

as another example, the Industrial Disputes Act of 1976 requires that written permission to retrench workers be obtained, normally from the relevant state government (Fallon and Lucas, 1991). Thus, practically, many countries worldwide implement what is known as "tenure" in universities, but across a large part of the economy.

What is the natural solution concept when markets are regulated, in particular when workers enjoy regulation related to employment security? The theoretical literature on matching seems to be mute about the possibility and implications of job security. In this work we revise the notion of stability so it accounts for a regulated labor market. In particular we would like to model a regulated market where firms cannot unilaterally fire employees (or where such costs of firing are prohibitively high). In such labor markets for a firm to be part of a blocking coalition it must account for its current employees and ensure their utility is not compromised. More simply, such a firm must retain its workers at their current salary level. Technically, such regulation implies fewer blocking coalitions and consequently the requirements underlying the implied notion of stability, which we refer to as JS-stability (where JS stands for Job Security) becomes easier to satisfy.

It is no surprise, therefore, that we can guarantee the existence of JS-stable outcomes in some markets where no stable outcomes exist. A key assumption for most results on labor markets is that of gross-substitutability. In the Kelso and Crawford model that we adopt, such gross-substitutability is a necessary and sufficient condition for a variety of results (see, among others, Kelso and Crawford (1982), Gul and Stacchetti (1999) and Ausubel (2006)). Our treatment, on the other hand, goes substantially beyond the scope of grosssubstitutability and allows for a broader class of preferences. In fact, existence and optimality of a JS-stable outcome is guaranteed for the class of 'Almost Fractionally Sub-additive' valuations (AFS), which we formally define in the sequel. Furthermore, it is shown that this class is a maximal class for which such existence and optimality of a JS-stable allocation hold.

The 'gross substitutes' assumption, and in fact any assumption on substitutability, obviously rules out the treatment of markets where complementarities exist among the workers. Such complementarity is vital for the analysis of many particular markets. Two leading examples are those of the matching between players and sports clubs — as clubs are focused on generating a team spirit and building synergy among their players — and of the matching between universities and academics.² The class of AFS production functions, which is

 $^{^{2}}$ As an example for this complementarity we note that this research might not have been conducted had Lavi and Smorodinsky or Fu and Kleinberg not been members of the same department.

central to our analysis, allows for some limited form of complementarity among workers (see Example 1) and so we can undoubtedly argue that our work goes beyond substitutability.³ In addition, it is straightforward to verify that the class of AFS production functions is a superset of the class of gross substitutes. In fact, it has been shown by Lehmann et al. (2006) to be substantially larger than the class of gross substitutes in some natural measure theoretic terms.⁴

In fact, the existence of stable outcomes under weaker notions of substitutability has received recent attention in the literature on matching with contracts. In particular, Hatfield and Kojima (2010) define two notions, 'bilateral substitutes' and 'unilateral substitutes', that extend the original substitutes condition of Hatfield and Milgrom (2005) and still ensure existence of stable outcomes. Sönmez and Switzer (2013) and Sönmez (2013) demonstrate the applicability of these extended classes in the context of the 'cadet-branch matching problem'. In order to interpret these classes within the original model of Kelso and Crawford (1982) one should embed the latter model in the former as follows. Consider the set of all contracts which are of the form of a triplet (m, n, s), interpreted as a contract where worker m is employed by firm n for the salary s. With this in mind it turns out that the classes of 'bilateral substitutes', 'unilateral substitutes' and 'gross substitutes' are one and the same and so the results of Hatfield and Kojima (2010) have no bite in the Kelso and Crawford model. This is no surprise given the maximality theorem of Gul and Stacchetti (1999) which argues that one cannot go beyond the class of 'gross substitutes' without considering weaker notions of stability as we do.

1.1 Our contribution

Our contribution is conceptual as well as technical.

- Our conceptual contribution is two-fold:
 - 1. We introduce a new solution concept for the many-to-many matching model JS-stability. This solution concept, tailored to analyze labor markets with employment protection, is inspired by the prevalence of regulation in many countries

 $^{^{3}}$ In the neoclassical matching literature, starting with Becker (1973), the assumption of complementarities (otherwise known as 'positive assortative matching') is cardinal for many of the results. Note that the notion of complementarities assumed in that literature is related to the synergy between a firm and a (single) worker. In contrast, we refer to complementarities among workers with respect to a firm's production function.

⁴Technically, for a natural measure over the set of all production functions, the set of all functions exhibiting gross-substitutes has measure zero while the class AFS has positive measure.

(in the EU in particular) which puts significant restrictions on firms' ability to fire employees. The on-going public debate of such regulation has not been part of the matching literature so far and JS-stability provides a (preliminary) means of such analysis.

- 2. We introduce a new class of production functions, dubbed 'almost fractionally subadditive' (AFS) functions. Recall that a production function is called submodular if it exhibits decreasing productivity. It is well-known that the class of submodular production functions strictly contains the class of gross-substitutes production functions (and in fact significantly expands it). Our class AFS strictly contains and significantly expands the class of submodular production functions.
- For these new concepts we prove the following theorems:
 - 1. We provide analogs of the welfare theorems to markets with job security. On the one hand, if firms' production functions are almost fractionally sub-additive (AFS) then any efficient outcome is sustained as a JS-stable outcome. On the other, although there may be inefficient JS-stable outcomes, we provide a tight bound on the efficiency loss such an outcome entails. In fact, in cardinal terms, summing over all players' utilities (as expressed with a numeraire good), the social welfare of any JS-stable outcome is at least 50% of the most efficient outcome.
 - 2. We show that the family of AFS production functions is maximal with respect to obtaining our welfare theorems.
 - 3. We provide a natural decentralized mechanism which yields a JS-stable outcome in equilibrium.

1.2 Literature on job security

The lion's share of the theoretical literature on job security and employment protection legislation makes use of partial and general equilibrium in dynamic models. A common thread of all these models is that the work force is assumed *homogeneous* (e.g., Gavin, 1986, Lazear, 1990, Acemoglu and Shimer, 2000, Bertola, 2004), which is in sharp contrast with our heterogeneity assumption. Typically, a firm's productivity depends on the size of the workforce but not on the exact composition of workers it employs. Whereas our model is static and with complete information these models are dynamic and information stochastically unravels with time (e.g., workers' productivity and firms' technology). Our paper also departs from the aforementioned body of literature in the main question posed. Whereas our focus is on existence and efficiency of a given solution concept (JSstability) the aforementioned body of literature primarily attempts to study the impact of the introduction and regulation of job security measures on the unemployment level. On the one hand job security implies that fewer employees are fired but on the other hand employers are more cautious in their hiring process and are reluctant to employ low productivity employees. The study of these two countervailing forces is an important common thread of previous work. Interestingly, the findings of this literature, both theoretically and empirically, are inconclusive. The exact nature of the model as well as the underlying assumptions, on the one hand, and the econometric model deployed, on the other hand, lead to conclusions which are often inconsistent with each other. The reader is referred to a survey by Bertola (1999) to learn more about this. Although our work does not discuss the impact of regulation around job security on unemployment rates we argue for the relevance of the new notion of stability to such an analysis. In particular, comparison of unemployment rates in stable vs. JS-stable outcomes may shed light on this important topic.

1.3 Other matching markets

The notion of JS-stability is primarily motivated by regulatory intervention designed to increase job security in labor markets. However, it may also have relevance in the study of immigration and community formation. In this context, matching takes place between countries on the one hand and citizens on the other hand. Thus, firms are replaced by countries and workers by citizens. In such a matching market there is also clear asymmetry in the flexibility to divorce. Typically, once citizenship is granted to someone it is (almost) impossible to revoke. On the other hand, although there exists a barrier for citizens to immigrate and replace their current citizenship with a different one such a barrier is clearly lower (which can be evidenced empirically). Thus, a variant of JS-stability to such a NTU setting may correctly represent the feasible community structure in a model of immigration.⁵ In fact, there may be additional many-to-many matching markets where divorce costs on both sides of the market are highly asymmetric and so the notion of JS-stability becomes an adequate tool for their analysis.

⁵We thank Yoram Weiss for pointing out this connection between JS-stability and community formation.

1.4 Paper structure

Section 2 introduces the model and details the new solution concept as well as the class of production functions we study. One particular aspect of our model is that each worker requires a minimal wage in order to work for any given firm. These minimal wages not only differ across workers but may differ across firms for any given worker and so the model is quite asymmetric. Section 3 focuses on a special case of our model where such asymmetry does not exist and the minimal wage is set to zero for all workers and all firms. It furthermore shows that this reduction is technically meaningless and results which are true for the special case are true for the more general model with asymmetry. Section 4 provides the main results, and Section 5 discusses future research.

2 Model

A labor market is composed of a set of N firms and M workers such that each firm hires as many workers as it wishes, but each worker is allowed to work only at one firm. Each firm pays its workers a salary and the utility of each worker depends on which firm he works for and the salary he receives. The firms' objective function is their profit and each firm's profit is the difference between the value of its production (in salary units) and the salaries it pays out. Note, in particular, there are no externalities among workers nor among firms.

The formal model we use is due to Kelso and Crawford (1982) — A labor market is a tuple (N, M, v, b) where N is a finite set of firms and M is a finite set of workers with quasi-linear utility function (in the sequel we abuse notation and use N and M to denote the cardinality of these sets as well). $v = \{v^n\}_{n \in N}$, where $v^n : 2^M \to \Re_+$ is firm n's monotonically increasing production function, as measured in the same units as salaries.⁶ We calibrate $v^n(\emptyset) = 0$. $b = \{b_m^n\}_{m \in M, n \in N}$, where $-b_m^n$ is the valuation, in salary terms, of worker m for working at firm n without being paid. In fact we typically think of b_m^n as the minimal salary requested by worker m for working at firm n and hence the negation sign. Thus, the quasi-linear utility for this worker is $u_m(n, s) = s - b_m^n$ when her salary is s.⁷ Hereinafter firm 0 will denote

 $^{{}^{6}}v^{n}$ is monotonically increasing if $C \subset D \implies v^{n}(C) \leq v^{n}(D)$.

⁷The model and results in Kelso and Crawford (1982) make use of an abstract utility function for workers, not necessarily of a quasi-linear form. In particular the units of such functions are abstract utilities in contrast with our quasi-linear functions whose units are in salary terms. Thus, as opposed to the Kelso-Crawford model, we can discuss a cardinal measure of social welfare and consequently measure efficiency levels, which is central to our results. However, we do so without ignoring non-salary related components of the workpackage as these are embedded in the minimal salary component (b in our model) which is dependent on the

unemployed workers and we calibrate $b_m^0 = 0$ for all m.

As productivity is measured in salary units, the profit of firm n from employing a set of workers C when workers' salaries are $\{s_m\}_{m \in M}$ is $\Pi^n(C; s) = v^n(C) - \sum_{m \in C} s_m$. We often abbreviate the tuple (N, M, v, b) to (v, b) as the sets of workers and firms are implicitly encoded in (v, b).

For any two disjoint sets of employees, C and D, we denote by $v(D|C) = v(D \cup C) - v(C)$ the marginal productivity of D given C and we also abuse notation and write m to denote the singleton set $\{m\}$ as well (hence v(m) will denote the productivity of a single worker, m).

An assignment of workers is a partition $A = \{A^0, A^1, \ldots, A^N\}$ of the set of workers, where A^n denotes all workers employed by firm n, with A^0 interpreted as the set of unemployed workers.

An allocation is a pair (A, s) where A is an assignment of workers and $s \in \Re^M_+$ is a vector of salaries. Such an allocation implies that any employee $m \in A^n$ works for firm n at a salary s_m , whenever n > 0 and $m \in A^0$ implies that m is unemployed and receives no salary.

Definition 1. An allocation (A, s) is *individually rational* (IR) if $(1) v^n(A^n) - \sum_{m \in A^n} s_m \ge 0 \quad \forall n \in N$; and $(2) s_m \ge b_m^n$ for all $n \in N$ and $m \in A^n$.

The first part of this definition requires that each firm has a non-negative net profit and the second part requires that each employed worker is paid her minimal required salary.

2.1 Stability and Job Security

The central solution concept we adopt is that of stability. However our notion of stability is a central innovation of our work and is weaker than the standard stability notions in two-sided markets. The stability notion we introduce is inspired by markets where job security is guaranteed by regulatory means. In particular, we consider the following simple yet somewhat extreme assertion - once a worker is employed by a firm for a certain salary only the worker can decide to quit whereas the firm cannot lower the salary nor can it fire the worker. Thus, the stability notion we introduce is an adaptation of the standard notion of stability to such regulatory restrictions. Formally:

Definition 2. A coalition $\{n, C\}$ is a **blocking** coalition for an allocation (A, s) if and only if $C \subset M \setminus A^n$ and there exists a vector of salaries, $\hat{s} \in \Re^M_+$, such that:

specific worker and the specific firm.

- $u_m(n, \hat{s}_m) \ge u_m(k, s_m) \quad \forall k \in N, m \in A^k \cap C \text{ (workers in } C \text{ are better-off)},$
- $v^n(C|A^n) \ge \sum_{m \in C} \hat{s}_m$ (firm *n* is better-off),

with at least one of the inequalities being strict.

The following alternative definition of a blocking coalition is more intuitive although less convenient for the proofs that follow:

Definition 3. A coalition $\{n, \hat{C}\}$ is a **JS-blocking** coalition for an allocation (A, s) if and only if $A^n \subset \hat{C}$ and there exists a vector of salaries, $\hat{s} \in \Re^M_+$, such that:

- $u_m(n, \hat{s}_m) \ge u_m(k, s_m) \quad \forall k \in N, m \in A^k \cap \hat{C},$
- $v^n(\hat{C}) \sum_{m \in \hat{C}} \hat{s}_m \ge v^n(A^n) \sum_{m \in A^n} s_m,$

with at least one of the inequalities being strict.

The classical notion of a blocking coalition, as in Kelso and Crawford (1982), is similar to the above definition except it does not require that $A^n \subset \hat{C}$. The connection between these two definitions is as follows:

Lemma 1. Let $C \subset M \setminus A^n$. The coalition $\{n, C\}$ is a blocking coalition for the allocation (A, s) if and only if $\{n, A^n \cup C\}$ is a JS-blocking coalition for the allocation (A, s).

Proof. Note that, without loss of generality, we may assume that $\hat{s}_m = s_m$ for any $m \in A^n$ in the definition of JS-blocking. With this at hand the proof is immediate.

Definition 4. An allocation (A, s) is called *Job Security stable (JS-stable)* if it is IR and there exist no blocking coalitions.⁸

In words, the requirement for JS-stability, beyond IR, is that there exists no firm and no set of agents currently not working for this firm such that the firm can offer better working terms for these agents (first set of inequalities) while maintaining its current set of workers

⁸Arguably, one could consider a stronger notion of stability where blocking coalitions may involve more than a single firm. To demonstrate this consider the JS-stable allocation of example 2. Note that by switching between workers b and c we improve the firms' utility without jeopardizing any of the workers. This suggests that for an alternative notion of a blocking coalition, involving more than a single firm, the allocation in the example might not be stable. We re-visit this issue in our concluding remarks where we introduce the JS-Core.

⁹Requiring individual rationality as part of the definition of JS-stability implies that a firm that is not profitable, and thus in danger of bankruptcy, need not comply with job security regulation.

and increasing its profits (second inequality). This is a weaker notion than the core allocation defined by Kelso and Crawford (1982). While Kelso and Crawford require that an allocation be immune to a deviation by a coalition of workers and a firm where such workers may (partly) replace the firm's current working force, our notion ignores this possibility as it is banned by regulation.

JS-stability models an extreme version of regulation related to job security. Thus, the inefficiency induced under JS-stability may be seen as a lower bound on the efficiency implications of some more realistic regulation. Indeed, as we demonstrate in this work, in spite of our modeling choice, efficiency partly prevails. This suggests that weaker forms of regulation designed for job security do not necessarily contradict efficiency.

2.2 AFS production functions

Throughout the paper we assume a certain structure on the production technology of each of the firms. To define this structure we recall the following definition from cooperative game theory: For any $C \subseteq M$, a vector of non-negative weights $\{\lambda_D\}_{D\subseteq C, D\neq\emptyset}$ is a "fractional cover" of C if for any $m \in C$, $\sum_{\{D\subseteq C:m\in D\}} \lambda_D = 1$.¹⁰ An example of a fractional cover of the set $\{a, b, c\}$ is $\lambda_D = \frac{1}{2}$ for any subset with two workers and $\lambda_D = 0$ otherwise.

Definition 5. A firm's production function v is *Fractionally Sub-additive on* $C \subseteq M$ if for any fractional cover $\{\lambda_D\}_{D\subseteq C, D\neq \emptyset}$ of C, $v(C) \leq \sum_{D\subseteq C, D\neq \emptyset} \lambda_D v(D)$.

To understand the intuition behind this notion assume a firm can either make use of the set C of workers during a single period or it can break C into subsets of workers (possibly overlapping) and deploy the subsets sequentially, each for a fraction of a period, such that any employee works a full period of time. The production function is fractionally sub-additive on C if the latter option is always at least as productive as the former. In the example of a fractional cover preceding Definition 5, the firm will (weakly) prefer having the three workers work in three shifts of pairs, each for half of a time period, over employing all three workers simultaneously for a single time period.

Definition 6. A firm's production function v is *Fractionally Sub-additive*, denoted $v \in FS$, if for any $C \subseteq M$, v is Fractionally Sub-additive on C.¹¹

¹⁰The term used in cooperative game theory is "balanced collection of weights", see Osborne and Rubinstein (1994).

¹¹Originally, a similar notion was introduced by Bondareva (1963) and Shapley (1967) in the context of value functions for cooperative games. However, Bondareva and Shapley actually take interest in the reversed inequalities and refer to such value functions as *balanced*.

Definition 7. A vector of salaries, s, is called a *supporting salary vector* for the production function v and a subset of workers $C \subset M$ if (1) $\sum_{m \in C} s_m = v(C)$; and (2) For any $D \subset C$, $\sum_{m \in D} s_m \leq v(D)$.¹²

A well known result relating these two concepts is the Bondareva-Shapley Theorem:

Theorem 1 (Bondareva-Shapley Theorem). v is Fractionally Sub-additive on $C \subseteq M$ if and only if there exists a non-negative supporting vector of salaries for v on C.¹³

We expand the class of production functions beyond FS as follows:

Definition 8. A firm's production function v is Almost Fractionally Sub-additive, denoted $v \in AFS$, if:

1. For any $C \subset M$ (excluding C = M) v is Fractionally Sub-additive on C; and

2.
$$v(M) \leq \frac{\sum_{m \in M} v(M \setminus m)}{|M| - 1}$$

Clearly $FS \subset AFS$.

Throughout the paper we focus on this new class of production functions. One thing to note is that, in contrast with the class of of production functions that exhibit Gross Substitutes (GS) which is most prevalent in the labor market literature, AFS may exhibit complementarities. This is demonstrated in the following example:

Example 1. Assume there are 3 workers, denoted a, b, c and let the production function u be defined by: u(a) = u(b) = u(c) = 3, $u(\{a, b\}) = u(\{a, c\}) = 6$, $u(\{b, c\}) = 4$, $u(\{a, b, c\}) = 8$. We leave it to the reader to verify that $u \in AFS$ (but not in FS). Note that the worker a and the pair $\{b, c\}$ are complementarities.

Note that the complementarity displayed in Example 1 is possible as we do not require the fractional sub-additivity to hold on the full set of workers but only on strict subsets.

A technical observation about functions in AFS which we use in the sequel is:

Lemma 2. $v \in AFS \implies \sum_{m \in M} v(m|M \setminus m) \le v(M) \le \sum_{m \in M} v(m).$

 $^{^{12}}$ Originally, Bondareva (1963) and Shapley (1967) consider the case where these inequalities are reversed and refer to a collection of such vectors as the *core* of a cooperative game

¹³Bondareva and Shapley actually prove that the core is not empty if and only if the value function is balanced, which is equivalent to the stated theorem.

Proof. To prove the left inequality note that:

$$\sum_{m \in M} v(m|M \setminus m) = \sum_{m \in M} v(M) - v(M \setminus m) = |M| \cdot v(M) - \sum_{m \in M} v(M \setminus m) \le |M| \cdot v(M) - (|M| - 1) \cdot v(M),$$

where the last inequality follows from the definition of AFS. Thus, $\sum_{m \in M} v(m|M \setminus m) \leq v(M)$.

To prove the right inequality we proceed by induction on |M|. The base, |M| = 1, is trivial. For |M| > 1,

$$v(M) \le \frac{\sum_{m \in M} v(M \setminus m)}{|M| - 1} \le \frac{\sum_{m \in M} \sum_{k \in M \setminus m} v(k)}{|M| - 1} = \sum_{k \in M} v(k),$$

where the second inequality follows from the induction hypothesis.

2.3 On a hierarchy of domains of production functions

In this section we remind the reader of additional domains of production functions which have been studied in the literature and we shed some light on how FS and AFS fit in the larger picture. This section is informal and provides no original definitions nor results. The reader can look up the formal definitions in various papers and in particular in Lehmann et al. (2006).

The most restricted class is that of Gross Substitutes, denoted GS and introduced by Kelso and Crawford (1982). A production function is in GS if, whenever it is optimal for the firm to hire a worker m at a given vector of salaries, it remains optimal to hire m whenever the salaries of workers other than m are increased while fixing the salary of m.

A production function v is called submodular if it exhibits decreasing marginal productivity. More formally, for every two sets of workers $S \subset T$ and for any worker $x \notin T$, $v(x|T) \leq v(x|S)$. We denote by SM the set of submodular production functions. Lehmann et al. (2006) show that $GS \subset SM \subset FS$ and consequently $GS \subset AFS$.

In fact, AFS is substantially larger than GS in the following sense. A production function can be represented by a vector in (2^M-1) -dimensional Euclidean space that specifies the value of the production function on every non-empty set. Under this representation, Lehmann et al. (2006) prove that the set GS has Lebesgue measure zero while SM (and consequently FSand AFS) have positive measure.

2.4 Efficiency

The efficiency level of an assignment A is $P(A) = \sum_{n} v^n(A^n) - \sum_{m \in A^n} b_m^n$ (recall that $v^n(\cdot)$ and b_m^n are all measured in salary units). An assignment is efficient if it maximizes the efficiency, over all possible assignments.

3 Salary Driven Workers

Before we state our results we consider a variation of a labor market which we refer to as labor markets with *salary driven* workers. We use the notion of 'salary-driven' to emphasize that workers do not care about any aspect of their job, except for their salary. This manifests itself by setting the minimal wage requested by all workers to zero, across all firms $(b_m^n = 0 \forall m \in M, n \in N)$.

For labor markets with salary driven workers the notions of individual rationality and JS-stability become simpler:

Lemma 3. Let $b_m^n = 0 \ \forall m \in M, n \in N$. An allocation (A, s) is individually rational (IR) if and only if $v^n(A^n) - \sum_{m \in A^n} s_m \ge 0 \ \forall n \in N$.

The proof is straightforward and therefore omitted.

Lemma 4. Let (A, s) be an allocation in a salary driven market (v, 0). Then (n, C) is a blocking coalition if and only if $v^n(C|A^n) > \sum_{m \in C} s_m$.

Proof. A sufficient condition: Clearly if $v^n(C|A^n) > \sum_{m \in C} s_m$ then by setting $\hat{s} = s$ the coalition (n, C) is a blocking coalition.

A necessary condition: Assume now that (n, C) is a blocking coalition and so there exits some vector of salaries \hat{s} such that $v^n(C|A^n) \ge \sum_{m \in C} \hat{s}_m$ and $\hat{s}_m \ge s_m \quad \forall m \in C$, with one of the inequalities being strict. Assume the strict inequality is $v^n(C|A^n) > \sum_{m \in C} \hat{s}_m$ then clearly $v^n(C|A^n) > \sum_{m \in C} s_m$ as well and we are done. If, on the other hand, $v^n(C|A^n) =$ $\sum_{m \in C} \hat{s}_m$ but for some $\hat{m} \in C$, $\hat{s}_{\hat{m}} > s_{\hat{m}}$ then once again we have $v^n(C|A^n) > \sum_{m \in C} s_m$ and we are done.

As before an allocation (A, s) is called *Job Security stable (JS-stable)* if it is IR and there exist no blocking coalitions.¹⁴

¹⁴The model of salary driven workers may be viewed as a combinatorial auction model with a seller who owns goods (the "workers") and buyers (the "firms") who have valuations for subsets of goods and compete for these goods. The interpretation of IR and efficiency in this model is straightforward, however the notion of a 'blocking coalition' and hence the notion of JS-stability forms a technical relaxation of the notion of a core for which the authors have compelling explanation.

3.1 Labor markets, without loss of generality, have salary driven workers

In this section we construct tools that will enable us to prove results about labor markets by restricting attention to labor markets that have salary driven workers. Let (v, b) be a labor market. We denote by (v - b, 0) a labor market with salary driven workers and production functions $(v - b)^n(B) = v^n(B) - \sum_{m \in B} b_m^n$. Similarly if (A, s) is some allocation then s - b is the following vector of salaries: If $m \in A^k$ then $(s - b)_m = s_m - b_m^k$.

Lemma 5. Let (v, b) be a labor market. $v^n \in AFS$ if and only if $(v - b)^n \in AFS$.

Proof. We prove the first direction and assume $v^n \in AFS$. To prove that $(v - b)^n \in AFS$ we need to show two things:

1. For any $C \subset M, C \neq M, v - b$ is fractionally Sub-additive on C. Indeed, let $\{\lambda_D\}_{D\subseteq C, D\neq \emptyset}$ be a fractional cover of C and so $\sum_{m\in C} b_m = \sum_{D\subseteq C, D\neq \emptyset} \lambda_D \sum_{m\in D} b_m$. Consequently:

$$(v-b)(C) = v(C) - \sum_{m \in C} b_m \le \sum_{D \subseteq C, D \neq \emptyset} \lambda_D v(D) - \sum_{D \subseteq C, D \neq \emptyset} \lambda_D \sum_{m \in D} b_m = \sum_{D \subseteq C, D \neq \emptyset} \lambda_D (v-b)(D).$$

2.
$$(v-b)(M) \leq \frac{\sum_{m \in M} (v-b)(M \setminus m)}{|M|-1}$$
. Indeed
 $(v-b)(M) = v(m) - \sum_{m} b_m \leq \frac{\sum_{m \in M} v(M \setminus m)}{|M|-1} - \frac{\sum_m \sum_{k \neq m} b_k}{|M|-1} = \frac{\sum_{m \in M} (v-b)(M \setminus m)}{|M|-1}.$

The opposite direction of the proof is similar and hence omitted.

Let $P_{(v,b)}(A)$ be the efficiency level of the assignment A for the labor market (v, b).

Lemma 6. $P_{(v,b)}(A) = P_{(v-b,0)}(A).$

Proof. This is quite straightforward:

$$P_{(v,b)}(A) = \sum_{n} (v^{n}(A^{n}) - \sum_{m \in A^{n}} b_{m}^{n}) = \sum_{n} (v-b)^{n}(A^{n}) = P_{(v-b,0)}(A).$$

Lemma 7. A is an efficient assignment for (v-b, 0) if and only if it is an efficient assignment for (v, b).

Proof. This follows directly from Lemma 6.

Lemma 8. The allocation (A, s) is an (IR) allocation for the labor market (v, b) if and only if (A, s - b) is an (IR) allocation for (v - b, 0).

Proof. Let (A, s) be an (IR) allocation for (v, b). Then, for each firm $n, v^n(A^n) \ge \sum_{m \in A^n} s_m$ which can be rewritten as $(v-b)^n(A^n) \ge \sum_{m \in A^n} (s_m - b_m^n) = \sum_{m \in A^n} (s-b)_m$. In addition, for each worker, $m, s_m \ge b_m^n$, where $m \in A^n$. Equivalently, $(s-b)_m \ge 0$ which means that (A, s - b) is (IR) in the labor market (v - b, 0).

The proof of the opposite direction is similar and hence omitted.

Lemma 9. The coalition (n, C) is a blocking coalition for the allocation (A, s) in the labor market (v, b) if and only if it is a blocking coalition for the allocation (A, s - b) in the labor market (v - b, 0).

Proof. Assume that (n, C) is a blocking coalition for the allocation (A, s) in the labor market (v, b). Then there exists some vector of salaries $\{\hat{s}_m\}_{m \in C}$ such that:

- $\hat{s}_m b_m^n \ge s_m b_m^k$ for all k and for all $m \in C \cap A^k$,
- $v^n(C|A^n) \ge \sum_{m \in C} \hat{s}_m$, implying $(v-b)^n(C|A^n) \ge \sum_{m \in C} \hat{s}_m b_m^n$

with at least one of the inequalities being strict.

Let us set $\bar{s}_m = \hat{s}_m - b_m^n$, $\forall m \in C$. The above system of inequalities is equivalent to:

- $\bar{s}_m \ge s_m b_m^k = (s-b)_m \quad \forall k \text{ and } m \in A^k \cap C,$
- $(v-b)^n(C|A^n) \ge \sum_{m \in C} \bar{s}_m,$

with at least one of the inequalities being strict, implying the desired conclusion.

The proof of the opposite direction is similar and hence omitted.

Lemma 10. The allocation (A, s) is a JS-stable allocation for (v, b) if and only if the allocation (A, s - b) is a JS-stable allocation for (v - b, 0).

Proof. This is a direct consequence of Lemmas 8 and 9.

4 Results

We now return to general labor markets and state our four main results. The first two connect JS-stability with efficiency and can be viewed as analogs for the First and Second Welfare Theorems. In particular, we show that whenever production functions are in AFS, efficient outcomes are JS-stable. In our third result we show that one cannot extend these results beyond the class of AFS production functions. Our final result makes a connection between the notion of JS-stability and, inspired by cooperative game theory, a Nash equilibrium of a natural auction-like non-cooperative game played among the firms. All these four results parallel central results in the literature on stability in labor markets. We informally summarize our results and their parallels towards the end of this section.

4.1 A $\frac{1}{2}$ -First Welfare Theorem

As one can expect, JS-stability does not guarantee efficiency. On the other hand the inefficiency of any JS-stable outcome is bounded:

Theorem 2. If (A, s) is a JS-stable allocation and \overline{A} is an efficient assignment, then $P(A) \geq \frac{1}{2}P(\overline{A})$.

Note that this result assumes no restrictions on production technologies.

Proof. We first prove our result for labor markets with salary driven workers, denoted (v, 0). Indeed, for every firm n we have $v^n(\bar{A}^n \setminus A^n | A^n) \leq \sum_{m \in \bar{A}^n \setminus A^n} s_m$. Thus, we have

$$v^n(\bar{A}^n) \le v^n(\bar{A}^n \cup A^n) \le \sum_{m \in \bar{A}^n \setminus A^n} s_m + v^n(A^n)$$

Therefore

$$\sum_{i=1}^{n} v^{n}(\bar{A}^{n}) \leq \sum_{i=1}^{n} \left(\sum_{m \in \bar{A}^{n} \setminus A^{n}} s_{m} + v^{n}(A^{n}) \right) \leq \sum_{i=1}^{n} \left(\sum_{m \in \bar{A}^{n}} s_{m} + v^{n}(A^{n}) \right) \leq \sum_{m \in M}^{n} s_{m} + \sum_{i=1}^{n} v^{n}(A^{n}) = \sum_{i=1}^{n} \sum_{m \in A^{n}} s_{m} + \sum_{i=1}^{n} v^{n}(A^{n}) \leq 2 \sum_{i=1}^{n} v^{n}(A^{n}),$$

where the last inequality follows from (IR) of the assignment $A = (A^n)_{n \in N}$. This proves the claim for labor markets with salary driven workers.

Now let (A, s) be a JS-stable allocation for an arbitrary labor market (v, b) and let A be an efficient assignment for (v, b). Therefore, (A, s - b) is a JS-stable allocation for (v - b, 0)(Lemma 10) and \overline{A} is efficient for (v - b, 0) (Lemma 7). Now:

$$P_{(v,b)}(A) = P_{(v-b,0)}(A) \ge \frac{1}{2}P_{(v-b,0)}(\bar{A}) = \frac{1}{2}P_{(v,b)}(\bar{A}),$$

where the left and right equalities follow from Lemma 6 and the inequality follows from the first part of the proof. $\hfill \Box$

This bound on the efficiency loss is tight as suggested by the following example:

Example 2. Consider a labor market with four salary-driven workers a, b, c, d and two firms with production functions, v_1 , v_2 , defined as follows. For any non-empty subset of workers $S \subseteq \{a, b, c, d\}$, $v_1(S)$ is 1 unless $\{a, c\} \subseteq S$, in which case $v_1(S)$ is 2; similarly, $v_2(S)$ is 1 unless $\{b, d\} \subseteq S$, in which case $v_2(S)$ is 2.

Let $S_1 = \{a, b\}$, $S_2 = \{c, d\}$ and set wages p(b) = p(c) = 1, p(a) = p(d) = 0. It is straightforward to verify this is a JS-stable allocation and the social welfare is 2, whereas the social welfare of the efficient assignment is 4.

4.2 A Second Welfare Theorem

Theorem 3. Let (v, b) be a labor market. If $v^n \in AFS$ for all $n \in N$ then for any efficient assignment A there is a salary vector s, such that (A, s) is a JS-stable allocation.

Note, in particular, that the existence of a JS-stable outcome is guaranteed under the conditions of Theorem 3

Proof. We begin by proving our result for an arbitrary salary driven labor market (v, 0), with production functions in AFS.

Case 1: No efficient assignment assigns all workers to a single firm: Therefore if $A = (A^1, \dots, A^n)$ is some efficient assignment then $A^k \neq M$ for any firm k. Thus, we can apply Theorem 1 (which is our version of the Bondareva Shapley theorem) and conclude that for each $k \in N$, there exists a supporting vector of salaries, $\{s_m^k\}_{m \in A^k}$, for (v^k, A^k) . For any $m \in M$ let n(m) denote the firm for which $m \in A^{n(m)}$ and set $s_m =$ $s_m^{n(m)}$. We show that the allocation (A, s) is JS-stable. IR follows immediately from the definition of a supporting vector of salaries. To finish our proof we must show that an arbitrary coalition, (n, B), where $B \subset M \setminus A^n$, cannot be a blocking coalition. Denote
$$\begin{split} R^k &= A^k \cap B. \text{ As } A \text{ is efficient } v^n(A^n \cup B) + \sum_{k \neq n} v^k(A^k \setminus R^k) \leq \sum_{k \in N} v^k(A^k). \text{ Therefore } \\ v^n(A^n) + v^n(B|A^n) &\leq \sum_{k \in N} v^k(A^k) - \sum_{k \neq n} v^k(A^k \setminus R^k) = v^n(A^n) + \sum_{k \neq n} v^k(R^k|A^k \setminus R^k). \text{ As } \\ \{s^k_m\}_{m \in A^k} \text{ is a vector of supporting salaries for } (v^k, A^k) \text{ we have } v^n(B|A^n) \leq \sum_{k \neq n} v^k(R^k|A^k \setminus R^k). \\ R^k) &\leq \sum_{k \neq n} \sum_{m \in R^k} s^k_m = \sum_{m \in B} s_m, \text{ implying that } (n, B) \text{ is not a blocking coalition.} \end{split}$$

Case 2: There is an efficient assignment that assigns all workers to firm n: Efficiency implies that for any $k \neq n$ and any $m \in M$, $v^k(m) + v^n(M \setminus m) \leq v^n(M) = v^n(m|M \setminus m) + v^n(M \setminus m)$, therefore $v^k(m) \leq v^n(m|M \setminus m)$.

Now set $s_m = v^n(m|M \setminus m)$ for every $m \in M$. We show that this yields a JS-stable allocation:

- IR: By Lemma 2 $v^n(M) \ge \sum_{m \in M} v^n(m|M \setminus m) = \sum_{m \in M} s_m$, and IR follows from Lemma 3.
- No blocking coalition: For every firm $k \neq n$ and for every subset $B \subseteq M$, we apply Lemma 2:

$$v^k(B) \le \sum_{m \in B} v^k(m) \le \sum_{m \in B} v^n(m|M \setminus m) = \sum_{m \in B} s_m,$$

Thus no blocking coalition follows from Lemma 4.

So far we have proven our claim for a salary driven labor market. The proof for an arbitrary labor market follows from Lemmas 5, 7 and 10. $\hfill\square$

Note that the proof of Theorem 3 is constructive and so it is suggestive of an algorithm that, given an efficient allocation, computes the salaries that support it as a JS-stable outcome.

4.3 The maximality of the set of production technologies AFS

We now turn to show that the set of production functions, AFS, is maximal with respect to the property that any efficient assignment can also be supported as a JS-stable allocation. In other words, if one of the firms has a production function that is not in AFS it could be the case that some efficient assignment is not supported by a JS-stable allocation. In fact, we will show that it could be that none of the efficient assignments are supported by a JS-stable allocation. Formally:

Theorem 4. If $\bar{v} \notin AFS$ then there exists a labor market (v, 0), where $v^1 = \bar{v}$ and for all n > 1 $v^n \in AFS$ and if A is an efficient assignment then for no vector of salaries s is (A, s) a JS-stable allocation of the market (v, 0).

Theorem 4 argues that AFS is a maximal domain of production functions such that the second welfare theorem holds. In particular if $v \in AFS$ then a JS-stable outcome is guaranteed to exist. However, Theorem 4 does not argue maximality of AFS with respect to the existence of JS-stable outcomes (that are not necessarily efficient). We take a slight detour before returning to prove Theorem 4 and show that such general existence cannot be guaranteed outside the class of Symmetrically Fractionally Sub-additive (SFS) functions, defined as follows:

Definition 9. A valuation v is called symmetrically fractionally sub-additive if for any $B \subseteq M$ with $|B| \ge 2$, $v(B) \le \frac{1}{|B|-1} \sum_{x \in B} v(B \setminus x)$. Let SFS denote the set of all symmetric fractionally sub-additive valuations.

An example of a symmetrically fractionally sub-additive function is production function, v, that satisfies $v(B) = \max\{v(x) : x \in B\}$ for any $B \subseteq M$. In words, a coalition can only produce as much as its top producing member. Such production functions are called *unit demand* production function.

Clearly $AFS \subset SFS$. In addition:

Lemma 11. $v \in SFS \implies \sum_{m \in M} v(m|M \setminus m) \le v(M) \le \sum_{m \in M} v(m).$

Note that this result is similar to Lemma 2 and in fact the proof of Lemma 2 applies verbatim to this lemma as well and so the proof is omitted.

With this at hand we turn to the following proposition that sheds some light on the structure of maximal domains which guarantee the existence of JS-stable allocations:

Proposition 1. If $u \notin SFS$ then there exist unit-demand production functions $v_1, ..., v_n$ such that the salary driven labor market with n + 1 workers, $((v_1, ..., v_n, u), 0))$, does not admit a JS-stable allocation.

Proof. Since $u \notin SFS$, Lemma 11 implies that there exists $B \subseteq M$ such that $\sum_{x \in B} u(x|B \setminus x) > u(B)$. We construct the following tuple of unit-demand valuations. For every worker $x \in M \setminus B$ we have two unit-demand valuations $v_x^{(1)} = v_x^{(2)}$ such that $v_x^{(i)}(x) = u(M) + 1$ and $v_x^{(i)}(y) = 0$ for any worker $y \neq x$. Additionally define a unit-demand valuation v_B as follows. Choose a small enough $\epsilon > 0$ such that (i) $\sum_{x \in B} (u(x|B \setminus x) - \epsilon) > u(B)$, and (ii) $\forall x \in B$ such that $u(x|B \setminus x) > 0$, $\epsilon < u(x|B \setminus x)$. Then define

$$v_B(x) = \begin{cases} \max(0, u(x|B \setminus x) - \epsilon) & x \in B \\ 0 & x \notin B \end{cases}$$

We show that that there does not exist a JS-stable allocation for this labor market. Note that in every possible JS-stable allocation in this labor market, every worker $x \in M \setminus B$ must be allocated to either the firm with valuation $v_x^{(1)}$ or $v_x^{(2)}$ and its salary must be $v_x^{(1)}(x)$. As a result, note that if in some JS-stable allocation a firm with valuation $v_x^{(i)}$ is being allocated some worker $y \in B$, y's salary must be zero. Suppose by contradiction that there exists a JS-stable allocation with salaries p and in which the firm with valuation u is allocated a set of workers T_u , the firm with valuation v_B is allocated a set of workers T_v , and $T_u \cup T_v \subseteq B$.

If $T_v = \emptyset$ or $v_B(T_v) = 0$ (in which case $p(T_v)$ is 0), then we have $p(B) = \sum_{x \in T_u} p_x \le u(T_u) \le u(B) < \sum_{x \in B} (u(x|B \setminus x) - \epsilon)$. Thus, there exists a worker $x \in B \setminus T_v$ with $p_x < u(x|B \setminus x) - \epsilon \le v_B(x)$. Since in this case the firm with valuation v_B will desire such a worker x, this cannot be a JS-stable allocation.

Otherwise, $v_B(T_v) > 0$. Let $x^* = \arg \max_{x \in T_v} v_B(x)$, then $v_B(x^*) = u(x^*|B \setminus x^*) - \epsilon$. Since $p(B \setminus T_u) = p(T_v) \le v_B(x^*)$ we have,

$$u(B \setminus T_u | T_u) - p(B \setminus T_u) > u(B \setminus T_u | T_u) - u(x^* | B \setminus x^*)$$
$$= (u(B) - u(T_u)) - (u(B) - u(B \setminus x^*))$$
$$= u(B \setminus x^*) - u(T_u) \ge 0,$$

where the last inequality follows since $T_u \subseteq B \setminus x^*$. Once again this contradicts the assumption that the allocation is JS-stable.

We now turn to some interim observations needed in order to prove Theorem 4:

For any valuation v and a positive number r let v + r be the valuation defined as follows: $(v + r)(D) = v(D) + r, \forall D \subseteq M.$

Lemma 12. For any monotone valuation v, there exists some positive number R such that for any $r \ge R$, $v + r \in FS$

Proof. If v(M) = 0, then v is already in FS. Otherwise, let R be (|M| - 1)v(M), and we show for any r > R, $v + r \in FS$, by constructing supporting salary vectors for every $S \subseteq M$ (Definition 7). For any $S \subseteq M$, consider the vector $s \in \mathbb{R}^S$, where $s_x = \frac{r+v(S)}{|S|}$, for each $x \in S$. It is straightforward to see that $\sum_{x \in S} s_x = r + v(S) = (v + r)(S)$. Then for any proper subset $T \subsetneq S$,

$$(v+r)(T) \ge \sum_{x \in T} \frac{r}{|T|} = \sum_{x \in T} r \cdot \frac{|S|}{|T|} \cdot \frac{1}{|S|} \ge \sum_{x \in T} r \left(1 + \frac{1}{|M| - 1}\right) \cdot \frac{1}{|S|} \ge \sum_{x \in T} \frac{r + v(S)}{|S|} = \sum_{x \in T} s_x$$

In the second inequality we used the fact $\frac{|S|}{|T|} \ge \frac{|M|}{|M|-1}$, and in the last inequality we used the fact $r > R \ge (|M| - 1)v(S)$. This shows that indeed s is a supporting salary vector, and therefore v + r is in FS by Theorem 1.

For any $T \subset M$ let $v|_T(\cdot)$ denote the restriction of $v(\cdot)$ to T.

Lemma 13. If $v \notin FS$ and for any proper subset $T \subset M$, $v|_T \in FS$ then for any proper subset $T \subset M$, v(T) < v(M).

Proof. For the sake of contradiction, suppose for $T \subsetneq M$, v(T) = v(M). By the assumption that $v|_T$ is in FS, there exists a supporting salary vector s on T. We extend s by padding 0 for all elements in $M \setminus T$ and argue that we obtain a supporting salary vector for M, contradicting $v \notin FS$. To see this, observe that $\sum_{x \in M} s_x = \sum_{x \in T} s_x = v(T) = v(M)$, and for any $S \subsetneq M$, $\sum_{x \in S} s_x = \sum_{x \in S \cap T} s_x \leq v(S \cap T) \leq v(S)$.

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We are now ready to prove Theorem 4:

Proof. (*Theorem* 4): We split the proof into two cases:

Case 1: If for some $B \subseteq M, \bar{v}(B) > \sum_{m \in B} \frac{\bar{v}(B \setminus m)}{|B| - 1}$ then the conclusion follows from Proposition 1.

Case 2: Assume that for all $B \subset M$, $\bar{v}(B) \leq \sum_{m \in B} \frac{\bar{v}(B \setminus m)}{|B| - 1}$. As $\bar{v} \notin AFS$ there exists some strict subset $T \subset M$ such that $\bar{v}|_T \notin FS$. In particular, let T be a minimal such subset, namely any strict subset of T is in FS. By Lemma 13 for any T' that is a strict subset of T, $\bar{v}(T') < \bar{v}(T)$. In particular we may choose $\bar{\epsilon} > 0$ be such that for any T' that is a strict subset of T, $\bar{v}(T') + \bar{\epsilon} < \bar{v}(T)$.

For any $\bar{\epsilon} > \epsilon > 0$ we define the valuation u^{ϵ} on M as follows: $u^{\epsilon}(D) = r - \bar{v}(D^{c}) \forall D \neq T^{c}$ and $u^{\epsilon}(T^{c}) = r - \bar{v}(T) + \epsilon$, where $r = r(\epsilon)$ is large enough to guarantee that $u^{\epsilon} \in FS$ (recall Lemma 12).¹⁵ Monotonicity of u^{ϵ} is straightforward from the construction and the choice of ϵ .

Allocating T to the firm with production function \bar{v} and T^c to the agent with production function u^{ϵ} is the unique optimal allocation. Note that it generates a social welfare of $r + \epsilon$ whereas any other allocation generates r.

Assume the theorem is false and that for any ϵ the unique optimal assignment of (\bar{v}, u^{ϵ}) can be supported by a JS-stable allocation $((T, T^c), s^{\epsilon})$. By IR $\sum_{m \in T} s_m^{\epsilon} \leq \bar{v}(T)$, however

¹⁵The set $D^c = M \setminus D$ denotes the complementary set of D in M.

by increasing the salary of some single worker in T we can assume, without loss of generality, that $\sum_{m \in T} s_m^{\epsilon} = \bar{v}(T)$.

For any $D \subseteq T$, JS-stability implies

$$\sum_{m \in D} s_m^{\epsilon} \ge u^{\epsilon}(D|T^c) = u^{\epsilon}(D \cup T^c) - u^{\epsilon}(T^c) = \bar{v}(T) - \bar{v}(T \setminus D) - \epsilon = \sum_{m \in T} s_m^{\epsilon} - \bar{v}(T \setminus D) - \epsilon.$$

Therefore, for any $D \subseteq T$, $\sum_{m \in T \setminus D} s_m^{\epsilon} \leq \bar{v}(T \setminus D) + \epsilon$. This can be equivalently stated as follows:

$$\sum_{m \in D} s_m^{\epsilon} \le \bar{v}(D) + \epsilon \quad \forall D \subseteq T.$$

Let $\bar{\epsilon} > \epsilon_n > 0$ be decreasing sequence with $\lim_n \epsilon_n = 0$ and let s be an accumulation point of the set of salary vectors $\{s^{\epsilon_n}\}_{n=1}^{\infty}$. Then $\sum_{m \in T} s_m = \bar{v}(T)$ and $\sum_{m \in D} s_m \leq \bar{v}(D) \quad \forall D \subset T$ which implies that s is a supporting vector of salaries for $\bar{v}|_T$ on the set T, contradicting the assumption that $\bar{v}|_T \notin FA$.

Note that the results of this section leave open the question of the maximal set of production functions that guarantee the existence of a JS-stable allocation. In particular, we do not know whether such an allocation necessarily exists in $SFS \setminus AFS$.

4.4 JS-stability as an outcome of a decentralized mechanism

A labor market, (v, b), naturally induces the following complete information normal-form game played among the firms. Each firm proposes a vector of salaries, one for each worker (and firm 0 proposes the vector **0**). Each worker is then assigned to the firm that proposed the best salary, while receiving a salary that would make him indifferent between his best offer and his second best offer. We refer to this game as the *Second-Price Item Bidding (SPIB)* game. Our last result shows that a JS-stable allocation is also an equilibrium outcome of the SPIB game.

Formally, each firm proposes a salary schedule $p^n = \{p_m^n\}_{m \in M}$. Given a vector of proposals $\vec{p} = (p^1, \ldots, p^N)$ and given a worker m, let $k_m = \arg \max_{n \in N \cup \{0\}} p_m^n - b_m^n$ and $s_m = \min\{s : s - b_m^{k_m} \ge p_m^n - b_m^n \forall n \ne k_m\}$.

Note that the existence of a pure Nash equilibrium is guaranteed. In fact, in any profile of bids where one firm proposes an "infinite" salary to all workers, while all other firms propose a minimal salary (one that makes workers indifferent between working and staying unemployed) is such an equilibrium. In what follows we rule out such equilibria by following ideas proposed in Christodoulou et al. (2008) and Bhawalkar and Roughgarden (2011). We restrict attention to Nash equilibria with no overbidding, which are those Nash equilibria, \vec{p} , in which, for any firm n and any subset of workers $D \subseteq M$, $v^n(D) \ge \sum_{m \in D} p_m^n$. In words, firms' proposals are such that they recognize no loss no matter which workers they are eventually assigned. In fact we consider here a weaker restriction which we refer to as Nash equilibria with weak no-overbidding, which are those Nash equilibria \vec{p} in which for any firm n, $v^n(D^n(\vec{p})) \ge \sum_{n \in D^n(\vec{p})} p_m^n$, where $D^n(\vec{p})$ is the set of workers actually assigned to firm n for the vector of proposals \vec{p} . In other words, the no-overbidding restriction involves only the set of workers the firm is eventually allocated. ¹⁶

Theorem 5. For any labor market (v, b) there exists a pure Nash equilibrium with weak no-overbidding in the induced SPIB game if and only if there exists JS-stable allocation in the market. Moreover, the underlying mapping between the NE and the JS-stable allocation preserves the assignment of workers to firms.

Proof. Let \vec{p} be a pure Nash equilibrium with weak no-overbidding for the SPIB game induced by (v, b). We construct a JS-stable allocation in the following way: the set of workers D^n assigned to firm n is exactly $D^n(\vec{p})$ the set of workers assigned to n in the equilibrium of the SPIB game. The salary of worker $m \in M$ will be $s_m = \max_{n \in N} p_m^n$. By definition, for every firm n and every $m \in D^n$, $p_m^n = s_m$. Thus, by weak no-overbidding, $v^n(D^n) \geq \sum_{m \in D^n} s_m$, implying the individual rationality requirement. Since \vec{p} is a Nash equilibrium, for any firm n and any $T \subset M \setminus D^n$, $v^n(T|D^n) \leq \sum_{m \in T} s_m$, since otherwise firm n can strictly increase utility in the SPIB game by proposing very high salary to the workers in T.

Now suppose that there exists a JS-stable outcome $((S_1, \dots, S_N), (p^1, \dots, p^N))$ for (v_1, \dots, v_N) . We claim that the following bid vector \vec{b} is a pure Nash equilibrium with weak no-overbidding for SPIB with (v_1, \dots, v_N) .

$$b_i^j = \begin{cases} p_j & j \in S_i \\ 0 & j \notin S_i \end{cases}$$

¹⁶To appreciate why weak no-overbidding is a significant relaxation of the no-overbidding criterion recall that production functions are not necessarily sub-additive. Thus, with weak no-overbidding a firm may end up with a profitable allocation of workers, for which there exists a partition of the allocated coalition of workers such that the sum of the bids over each element is larger than its productivity. This cannot occur with the original no over-bidding criterion and so the original no-overbidding condition may effectively limit the firms to bid very low (relative to their actual value) on certain sets of workers.

Note that with this bid vector, each player i wins S_i , and pays zero. Clearly player i cannot increase her utility by changing any bid for a worker in S_i , as she pays zero for these workers. She also cannot increase utility by bidding higher on workers in some subset $T \subset \Omega \setminus S_i$, as she will have to additionally pay $\sum_{j \in T} p_j \ge v_i(T|S_i)$ for these workers, where the inequality follows from JS-stability. Thus \vec{b} is indeed a Nash equilibrium. By individual rationality, $v_i(S_i) \ge \sum_{j \in S_i} p_j$, implying that \vec{b} satisfies weak no-overbidding, and the claim follows. \Box

4.5 Summary of Results

existing interature on unregulated labor markets:					
TYPE OF LABOR	UNREGULATED	REGULATED			
MARKET	(existing literature)	(our contribution)			
Solution concept	Stable allocations	JS-stable allocations			
Set of production function	GS	AFS and SFS			
First welfare theorem	Stable allocations are efficient.	JS-stable allocations obtain			
		half the maximal efficiency.			
Second welfare theorem	Pareto efficient allocations are	Efficient allocations are			
	stable in GS.	JS-stable in AFS.			
Maximality	Stable allocations are not	Efficient JS-stable allocations			
	guaranteed outside GS.	are not guaranteed			
		outside AFS.			
		JS-stable allocations are			
		not guaranteed outside SFS.			
Non-cooperative	Stable allocations are	JS-Stable allocations are			
foundations	Nash equilibria of the	Nash equilibria of the			
	first price item bidding game	second price item bidding game			
	(Bikhchandani, 1999).	(with no over-bidding).			

The following table informally summarizes our main results while comparing these with the existing literature on unregulated labor markets:

5 Discussion and Future Research

In this work we introduce JS-stability as a new solution concept for many-to-many matching markets. This concept is inspired by regulated labor markets where costs for firing employees are prohibitively high. Clearly any stable outcome, in the classical sense, is also JS-stable.

However, there are JS-stable outcomes which are not stable. In fact, there is a large family of production functions which do not admit stable outcomes, yet JS-stable outcomes not only exist for them but in fact support all efficient outcomes. Unfortunately, JS-stability does not always guarantee efficiency. Surprisingly, it does guarantee a (multiplicative) upper bound of 50% on efficiency loss.

5.1 Regulated labor markets

Harnessing the many-to-many matching model for studying regulation in labor markets is novel, to the best of our knowledge. Thus, our work must be viewed as the first step of a research agenda that studies implications of regulatory intervention in labor markets. We highlight some natural follow-up questions which we leave for future research:

• Unemployment rates: Much of the work done by labor theorists around termination costs for workers focuses on the implications of such costs on the unemployment level. Two contradicting forces come into play. First, due to high termination costs employees will not be fired and hence unemployment should decrease. Second, at the hiring stage firms take the termination costs into account and so tend to hire less. The lion's share of the related work uses partial or general equilibrium analysis. In particular it assumes a homogeneous workforce. Our model, on the other hand, assumes heterogeneity of the workers and so may lead to conclusions that are different from those reached via the homogeneity assumption. In future work we shall compare employment levels in stable outcomes with those of JS-stable outcomes, when both exist (e.g., under gross-substitutes assumption). It can be demonstrated that, in general, such comparative statics can swing both ways. Consider the market in the following example, due to Fuhito Kojima, where JS-stable outcomes exhibit lower unemployment levels combined with a lower social welfare, when compared with a stable outcome of the same market:

Example 3. There are two firms, A and B, and three workers a, b, c. Let $b_a^A = 1$ and $b_m^n = 0$ otherwise. Firm A has a unit demand and $v^A(a) = 0, v^A(b) = 1, v^A(c) = 1.5$. For firm B, $v^B(a) = 4, v^B(b) = 6, v^B(c) = 2$ and $v^B(X) = 6$ otherwise.

Note that matching b with B and c with A, both with zero salary, is a stable matching which leaves a unemployed. On the other hand matching b with A at a salary of 1, a and c with B at salaries 4 and 2 respectively, yields a JS-stable outcome with no unemployment (note that this matching is not efficient nor stable as B and b at a salary of 5 is a blocking coalition).

We leave it to the reader to find an example that demonstrates the opposite. Thus, one should refine the analysis and focus on specific domains of production functions where the outcome is conclusive. In addition, computing bounds on differences of unemployment under the two stability concepts is interesting. We leave these questions to future research.

- Severance payments: As mentioned, JS-stability is inspired by prohibitive firing costs for employers. For example, a recent trend in labor theory is to study the implications of a requirement for severance payments when firms layoff employees (e.g., as suggested in Blanchard and Tirole (2008)). In fact, some countries, like Denmark, already implement such a policy (Andersen, 2012). It will be interesting to replace the notion of JS-stability with an alternative solution concept which models more moderate regulation than tenure within the framework of many to many matching models. One thing to note is that the conclusions of such a model may also depend on the recipient of such severance payments. Does the employee or the state enjoy them (in which case they could be modeled as deadweight costs)? The research agenda may well go beyond severance payments and study other regulatory means designed for job protection and job security such as insurance institutions.
- Risk-averse workers: Recall that some of our results refer to a cardinal notion of efficiency. For this notion to make sense we require that all utilities, for firms and for workers, are given in the same 'currency'. As a result our model assumes that firms' and workers' utilities are given in terms of money. Whereas for firms this is natural (as we identify utility with profits), for workers this is a limitation. Therefore, a study of JS-stability is called for when workers' utility functions go beyond additive-separable functions. This is particularly important if one would like to account for uncertainty without assuming workers are necessarily risk neutral.

5.2 The structure of the set of JS-stable outcomes

Apart from the natural appeal of stability as a solution concept in matching models it also exhibits a very elegant mathematical structure, as the set of stable outcomes forms a lattice under a natural order. A variety of observations then follows. These observations may have natural counterparts when considering the larger set of JS-stabile outcomes:

• A basic question we leave open refers to the maximal class of production functions which guarantees the existence of a JS-stable outcome (albeit not necessarily an efficient

one). We do not know if there is a unique maximal such class of production functions, much less how to characterize the production functions in a maximal such class.

- Is there a similar lattice structure for the set of JS-stable outcomes? What kinds of production functions allow for such a lattice structure? We suspect that the answers will typically be negative but have not studied this in depth so far.
- A central corollary one can derive from the lattice structure of stable outcomes is the existence of 'best' and 'worst' stable outcomes for the firms as well as for the workers. However, such best and worst allocations may exist even without a lattice structure (e.g., see Hatfield and Kojima (2010)). Thus, the study of extreme allocations that are JS-stable may take place even prior to our full understanding of the existence of a lattice structure for JS-stable outcomes.

5.3 The JS-Core

The solution concept we focus on, JS-stability, is based on the inexistence of blocking coalitions composed of a single firm and some workers. However, a JS-stable allocation can conceivably allow for a situation where there exists a set of more than a single firm for which these firms can shuffle their current joint set of workers and possibly recruit additional workers to obtain an outcome that is better for all involved (the firms in the set, the current set of workers and the additional workers). Thus, the set of workers of such firms will happily agree with being laid-off, conditional on being recruited by some other firm in the set of firms. Such a possibility may imply that what we refer to as a JS-stable allocation may not necessarily be stable, even when Job-security provisions are instated.

This situation is demonstrated in the JS-stable outcome of Example 2 where two firms can switch workers, in particular workers b and c, and consequently improve the situation for all. This observation begs a definition of a stronger notion of stability, the *JS-core*:

Definition 10. Given an allocation (A, s), we say that a coalition composed of a set of firms $\hat{N} \subset N$, and a set of workers C such that $\bigcup_{n \in \hat{N}} A^n \subset C$, is a *big blocking coalition* if there exists an allocation (\hat{A}, \hat{s}) such that $\bigcup_{n \in \hat{N}} \hat{A}^n = C$ and:

- $u_m(n, \hat{s}_m) \ge u_m(k, s_m) \quad \forall k \in N, n \in \hat{N}, m \in A^k \cap \hat{A}^n \cap C$ (workers in C are better off in allocation (\hat{A}, \hat{s})),
- $v^n(\hat{A}^n) \sum_{m \in \hat{A}^n} \hat{s}_m \ge v^n(A^n) \sum_{m \in A^n} s_m$ for all $n \in \hat{N}$,

with at least one of the inequalities being strict.

Definition 11. An allocation (A, s) is in the Job Security Core (JS-Core) if it is IR and there exist no big blocking coalitions.

Dropping the requirement in Definition 10 that $\bigcup_{n \in \hat{N}} A^n \subset C$ gives the definition of the *Core*. Some immediate observations are:

Proposition 2. The following holds for the JS-Core:

- Any allocation in the JS-core is JS-stable.
- There are allocations that are JS-stable but are not in the JS-Core (see Example 2).
- Any allocation in the JS-core is Pareto optimal (otherwise the grand coalition is a blocking coalition).
- The Core is a subset of the JS-Core.

Consider an allocation that is JS-stable yet not in the JS-core. For the big blocking coalition to succeed in pulling off a deviation all changes must occur simultaneously or alternatively there must exist strong guarantees in place for a job for those workers who voluntarily leave their current employer as well as strong guarantees for firms who commit to hiring new workers that some of their current workforce will voluntarily quit. Such a set of cross guarantees may be highly unreasonable when more than a single firm is involved. Thus, although the study of the JS-Core may shed additional light on the regulatory implications of tenure, the notion of JS-stability makes for a reasonable starting point for such analysis.

5.4 Matching with contracts

The simple many-to-many matching model that we use was extended by Hatfield and Milgrom (2005) to a model of 'matching with contracts'. In such a model a contract between a firm and an agent may specify various aspects related to employment, beyond the salary. It may specify working hours, shifts, insurance, job description, and many more. Therefore there may exist many possible contracts between a worker and a firm. Consequently, the firm's output (and, consequently, its profit) will not depend only on the set of employees it employs but also on the specific contracts signed between the employees and the firm. Milgrom and Hatfield extend the results from the many-to-many matching model to the new matching-with-contracts paradigm under the gross-substitutes assumption. Echenique (2012) showed that under the gross substitutes assumption the two models are in fact equivalent and the seemingly multi-dimensional extension from wages to contracts boils down to a single-dimensional set. However, Hatfield and Kojima (2008; 2010) demonstrate the richness of the matching-with-contracts paradigm by extending some of the results beyond the familiar domain of gross substitutes. In particular they propose new notions of substitutability, called bilateral and unilateral substitutes. Sönmez and Switzer (2013) and Sönmez (2013) provide a realistic example of a market where these weaker assumptions hold and, as a result, offer new and more efficient allocation mechanisms for such markets.

A major component of our analysis is the domain of production function which we analyze. In particular this domain, *AFS*, goes far beyond gross substitutes. Thus, the matchingwith-contracts model is indeed a more general model and is not subject to the Echenique critique. Studying JS-stability in such a model is left to future research.

5.5 Auction theory

As noted frequently in the literature, matching models have natural connections with combinatorial auctions, where the buyers (the "firms") who have valuations for subsets of goods need to pay the sum of item prices (the "wages") in a bundle in order to keep the bundle. Our solution concept of JS-stability is then a relaxation of the Walrasian equilibrium in the auction context. A Walrasian equilibrium consists of allocations and item prices such that no bidder can improve her utility by adding items or dropping items or doing both. In comparison, equilibria corresponding to JS-stability would not allow bidders to drop items, although they are allowed to add items at current prices. If we refer to such equilibria as equilibria conditional on buying at least a pre-specified subset of items (abbreviated conditional equilibria), all of our results can be translated as properties of conditional equilibria. For example, the social welfare at a conditional equilibrium, whenever it exists, is always a 2-approximation to the optimal; the AFS valuation class is maximal with respect to the property that any welfare-optimal allocation can be supported as a conditional equilibrium. The SPIB game that we discussed in Section 4.4 corresponds to a natural *simultaneous* second-price item auction. In this auction, all bidders simultaneously submit their bids on all items, and then each wins the items on which she bids highest and pays the sum of second highest bids on those items. Previous work (Christodoulou et al., 2008; Bhawalkar and Roughgarden, 2011) showed that allocations at Nash equilibria with no overbidding in this auction give 2-approximation to the optimal social welfare when bidders' valuations are complement free. Our results immediately imply that for all valuations, as long as a Nash equilibrium under weak no-overbidding exists, it achieves a 2-approximation to the optimal social welfare. Our study also sheds light on the question of which valuation classes guarantee the existence of pure Nash equilibria in the simultaneous item auction.

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