Improving Societal Outcomes in the Organ Donation Value Chain

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The mismatch between the demand and supply of organs for transplantation is wide and results in significant socio-economic costs. We examine a unique principal-agent problem in the cadaver organ donation value chain (ODVC) where the principal in our case is a social planner that has an overall quality-adjusted-life-year (QALY) improvement objective. The agents include a non-profit organ procurement organization (OPO) with a volume-of-care objective and a for-profit hospital (trauma center). The main contributions of our work are two-fold: First, while the majority of the literature focuses on the demand side of an ODVC, we develop an analytical model and study the effects of contextual parameters and decisions of the supply-side entities in an ODVC on their respective payoffs as well as on societal outcomes. This model interrelates key components, including organ recovery reimbursement rates for the hospital, cost of inpatient waiting, shared operating room capacity where organ recovery and other inpatient procedures take place, and QALY increments for organ recipients as compared to the hospitals other patients. Our analysis highlights the misalignment in the objectives of the social planner, the non-profit OPO, and the for-profit hospital. Second, we recommend administratively feasible and Pareto-improving contracts (composite criteria-based and penalty-based) that a social planner can use to help the ODVC achieve socially-optimal performance. By showing the existence of a Pareto-improving contractual mechanism in our context, we illustrate the possibility for social value for the non-profit participants to not necessarily be at the expense of economic value for the for-profit participants.

Key words: healthcare operations; nonprofit operations; organ donation; contracts

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1. Introduction

The mismatch between supply and demand of organs for transplantation is significant: as of December 2014, over 123,000 individuals in the US were registered on the waitlist to receive an organ. This number is substantially large compared to supply-side figures: in 2013, there were 14,257 donors who accounted for 28,952 transplants (HRSA 2015). The wait for a kidney transplant from a cadaver donor can take up to seven years (Morrissey 2009), and about 7,000 patients die every year while waiting for a life-saving kidney transplant (HRSA 2015). US Medicare’s cost of maintaining a kidney transplant recipient is approximately $8,550/year as compared to $50,938/year per patient for dialysis (GAO Study 2007). Despite the creation of donor registries, the use of organs from expanded criteria donors, and improvements in surgical techniques, organ preservation, and immunosuppressant drugs, there is still a significant gap between the supply and demand for organs. This gap is compounded by the continuing drop in traumatic incidents and improved trauma care. We address this critical gap by studying the operational actions in the cadaver organ donation value chain (ODVC) involving a non-profit Organ Procurement Organization (OPO) with a volume-of-care objective, a for-profit hospital, and a social planner with a broader societal objective. The context of the cadaver ODVC presents unique challenges due to divergence in the objectives of the non-profit and for-profit entities.

We aim to address a principal-agent problem in the ODVC. The principal in our case is the social planner (Department of Health and Human Services, DHHS) that aims to optimize societal outcomes. The DHHS is the Federal Government’s agency for protecting the health of all US nationals and providing essential human services. We recommend a contractual mechanism to ensure that the agents, namely, the for-profit hospital – most typically, a trauma center – where cadaveric donors arrive and the non-profit OPO, make operational decisions that are in alignment with the social planner’s objective.
The OPO is a non-profit entity designated by the Federal Government to carry out the following main tasks in an ODVC: collaborate with hospitals in its service area, educate hospital staff on standard procedures for organ donation, follow-up on identified potential organ donors, request family authorization for organ donation in the case of medically acceptable organs, and coordinate recovery, matching, and transportation of recovered organs. In contrast, Anderson and Steinberg (1984) and Friedman and Pauly (1983) show that hospitals exhibit a profit-maximizing response to changes in reimbursement terms. Also, several studies, including Deneffe and Masson (2002) and Duggan (2000) show that non-profit hospitals behave in a similar manner as profit maximizing entities when responding to policy changes and increased competition. Thus, the hospital’s decision on allocation of resources for organ recovery activities is typically based on a for-profit objective.

Although the relationship between the OPO and the hospital is known to be important since both entities are essential to the supply side of the ODVC, several studies continue to emphasize the need for better coordination in order to alleviate the significant mismatch between organ recovery and demand (see, for example, Traino et al. (2012), who discuss barriers to the timely referrals of potential donors). We aim to answer the following research questions: (i) How do the operational actions of supply-side players in an ODVC impact their individual payoffs and societal outcomes? (ii) What kinds of mechanisms can be implemented by the social planner to improve societal outcomes in an ODVC, and to ensure that no player is worse off?

The study by Sheehy et al. (2003) shows that larger hospitals are more likely to have greater numbers of potential and actual donors – specifically, 19% of hospitals account for 80% of the donations. We therefore focus our analysis on a large hospital (most typically, a major trauma center) in the OPO’s donor service area (DSA). Also, similar to Zenios et al. (2000), Zenios (2002), we consider that the social planner would take into account
improvements in the quality of life of organ recipients after transplantation surgery; specifically, the social planner uses quality-adjusted life years (QALY) as a measure of health outcomes. Consequently, our model formulation is different from a typical supply chain coordination problem because the social planner’s payoff is different from the sum of the payoffs of the individual for-profit and non-profit players. The main contributions of our work are two-fold. First, we develop a model to study the effects of operational decisions of the supply-side players in an ODVC on their respective payoffs as well as on societal outcomes. The model reflects key contextual components, including organ recovery reimbursement rates for the hospital, cost of inpatient waiting, shared operating room (OR) capacity where organ recovery and other inpatient procedures take place, and increments in QALY for organ recipients as compared to the hospital’s other patients. Our results highlight a need for mechanisms to address the misalignment in the objectives of the individual players and the social planner. Second, we recommend administratively feasible and Pareto-improving contracts (composite criteria-based and penalty-based) that a social planner can use to align the operational actions of the OPO and the hospital to help the ODVC achieve socially-optimal performance.

Our findings have important implication for non-profit operations management. Several researchers have pointed out the prevalence of inefficiencies in supply chains in the presence of both non-profit and for-profit players. For example, Ergun et al. (2010) state that ambiguity related to decision making, incentive misalignment and absence of a single performance metric in humanitarian supply chains may lead to coordination problems and insufficient supply responsiveness. Porter and Kramer (2011) discuss the existence of the belief that companies must part away with economic success to make way for societal benefits. Contrary to the perception that regulatory measures by the social planner most often hurt the for-profit entities in socially-responsible supply chains, by showing the existence
of a Pareto-improving mechanism in our context, we illustrate the possibility for social value for the non-profit participants to not necessarily be at the expense of economic value for the for-profit participants.

The remainder of the paper is organized as follows: Section §2 presents related literature review. Section §3 explains the structure of the US Organ Procurement and Transplantation Network with a description of the functioning of OPOs and a discussion of the OPO–Hospital relationship. Section §4 presents our analytical model of the supply side of an ODVC, Section §5 includes our analytical results and Section §6 concludes the paper.

2. Literature Review

Our work draws on and contributes to three streams of literature. (i) The operations management (OM) literature that focuses on the demand and supply of organs in an ODVC. (ii) The literature on non-profit operations management and humanitarian supply chain operations that considers the distinctive features of not-for-profit operations. (iii) The medical literature on cadaveric donations that presents the perspectives of healthcare professionals and medical researchers in the field.

The majority of the OM literature focuses on the demand side of an ODVC. The demand for organs is known in the form of the national waitlist maintained by the United Network for Organ Sharing (UNOS). Several research studies have addressed the issue of optimal allocation of organs to waiting patients once an organ becomes available for transplantation. OM researchers have recommended various organ allocation policies to maximize social or individual welfare, with organ supply assumed to be exogenous (Alagoz et al. 2004, 2007, David and Yechiali 1995, Su and Zenios 2006, Zenios et al. 2000). Kreke et al. (2002) and Zenios et al. (2000) use simulation models and the UNOS database of previous organ transplantations to study the potential impacts of changes to the current organ allocation policy. A few recent studies focus on improving the supply of organs for transplantation,
e.g., by examining donation by *living* donors. For instance, Roth *et al.* (2007) show that three-way and two-way kidney exchanges between patients with incompatible living donors (e.g., blood- or tissue-type incompatibility between a patient needing an organ transplant, and a living donor) will lead to a substantial increase in the number of transplants.

To our knowledge, a working paper by Arikan *et al.* (2014) is the only other paper in the OM literature that discusses the supply side of organ transplantation from *cadaveric* donors. They perform an empirical study to study the key drivers of organ procurement rates and show that higher organ quality, longer waiting times for an organ in an OPO’s service area, and greater transplant center competition generate greater OPO “intent” to procure organs for transplantation. They also propose that – in order to increase the supply of deceased donor kidneys – low-quality organs should be made immediately available more widely, rather than sticking to geographical constraints that currently apply to all organs. Our work adds to this literature by studying the operational actions of the supply side players in the cadaver ODVC.

There is an emerging stream of literature in OM that recognizes the unique challenges and strategies associated with non-profit operations. A distinct feature of these supply chains is the set of objectives targeted by the for-profit versus the non-profit organizations (Tomasini and Van Wassenhove 2009). Bhattacharya *et al.* (2014) and Holgun-Veras *et al.* (2012) highlight the differences between humanitarian supply chains and traditional supply chains, including supply chain design requirements and coordination mechanisms. The divergence between individual and societal objectives in the ODVC similarly leads to unique interrelationships and coordination challenges. Further, Berenguer *et al.* (2014) highlight the lack of inter-organization collaboration as a recurring challenge in non-profit operations, which is true of our context as well. Ergun *et al.* (2014) utilize a cooperative game theoretic model to explore improvements in humanitarian operations through
collaboration among the different parties involved, such as government, private, and non-governmental organizations. Similar to their work, we utilize a game theoretic model to understand the interrelationships between the operational decisions and the respective payoffs of the non-profit and for-profit supply-side players in an ODVC.

We also draw on the medical literature to understand the views of the medical community on ways to alleviate the wide gap between the supply and demand of organs for transplantation. Traino et al. (2012) implemented a national test of the Rapid Assessment of hospital Procurement barriers in Donation (RAPiD, a qualitative needs assessment tool for identifying barriers to donor identification and referral, and to family requests for donation) and found that the hospital–OPO relationship has inherent tensions. The empirical study conducted by them revealed that the hospital–OPO dynamic is strained, as the individuals (i.e., health care professionals (HCPs)) caring for potential donors and trying to keep them alive are the same individuals on whom the system relies for referrals. Our work builds on their major recommendation, as also reiterated by several other researchers (see, Franklin et al. (2009) for an overview), that special efforts are required by the social planner to make sure that the non-profit OPO and for-profit hospital plan their efforts to ensure the successful conduct of organ recovery activities. Domingos et al. (2012) emphasize that the performance of organ donation systems must be considered as an index of the overall quality of care, as a means to improve organ recovery outcomes. They propose that not only OPOs but also intensive care units (ICUs) at hospitals should be evaluated on the conversion rate of potential donors to donors from whom organs are eventually recovered. Through our analytical model, we attempt to explore the possibilities of introducing contractual levers in order to better align the private objectives of the OPO and the hospital with the public objective of the social planner.
3. Overview of the Organ Procurement and Transplantation Network

Our analytical model is closely based on the existing functioning of the organ procurement and transplantation network (OPTN), of which the OPO, the hospital, and the social planner are all participants. Therefore, in this section we provide an overview of the network and the interactions among the participants that constitute our model.

3.1. Network Structure

The US OPTN was set up in 1984 to help ensure the success and efficiency of the US organ transplant system. All OPOs and transplant centers must be registered members of OPTN to receive funds from Medicare. UNOS is a non-profit organization that administers and maintains OPTN contracts. The Federal Government has divided the country into 11 regions that are further divided into donor service areas (DSAs). There are 69 OPOs and each OPO is assigned the task of recovering organs in all hospitals in its DSA. Willing patients in need of an organ join the waiting list. Organ allocation rules are fed into a computer algorithm to aid in the matching and allocation of organs. Each time an organ becomes available in the DSA of an OPO, relevant data related to the donor and organ is entered into the online allocation system. The system then generates a list of potential recipients for that specific organ. The OPO offers an organ sequentially down the list by communicating with the transplant surgeon at the transplant center where the matched patient is waitlisted. The transplant surgeon has to immediately acknowledge receipt of the offer followed by a quick decision as to whether to accept or decline the organ on behalf of the recipient patient. Once the OPO receives a positive intent from a transplant surgeon (or, from all transplant surgeons, if multiple organs are available from the same donor), preparations are made to surgically recover the organ(s) at the donor hospital. Recovered organs are preserved in medically requisite environments for transport to the recipient transplant centers.
3.2. Organ Procurement Organization (OPO)

An OPO is a non-profit organization having a contiguous geographical DSA designated by the Federal Government. The Health Resources and Services Administration (HRSA), an agency within DHHS that oversees the OPTN, utilizes a competitive contracting process to award contracts to OPOs to operate within the OPTN. The OPTN contract is a cost-share, cost-reimbursement contract. This is a contract in which the contractor (OPO) receives no fee and is reimbursed only for an agreed-upon portion of its allowable costs. Services furnished by OPOs in connection with organ acquisition and transplantation of kidneys are reimbursed by Centers for Medicare and Medicaid Services (CMS) after the determination of reasonable costs. CMS is an operating division of DHHS that administers Medicare, Medicaid, the Children’s Health Insurance Program, and clinical quality standards. Other sources of revenue for the OPO are payments made by recipient transplant centers (e.g., organ acquisition charges) and fundraising activities (e.g., philanthropic gifts). CMS certifies OPOs for four years. It measures OPO performance on a rolling basis (every six months) on multiple dimensions, including conversion rate (number of donors from whom organs are recovered as a percentage of potential donors), and organs recovered per donor. Per the Federal Government’s OPTN Member Evaluation Plan, an OPO’s failure to meet performance requirements can lead to CMS taking corrective actions ranging from requesting a plan for improvement to revocation of the OPO contract.

One of the key provisions of the revised Medicare conditions for organ donation (CMS Ruling 42 CFR 482 on June 22, 1998), also termed as the “donation rule,” is that hospitals must contact their OPO in a timely manner about individuals whose death is imminent or who have died while in the hospital’s care. OPOs typically provide hospital nurses with a “trigger card” displaying criteria pertaining to the health condition of the patient, which when met indicate that the patient could be a potential organ donor and that the OPO should be contacted (see Appendix A for an example of a trigger card).
Once a referral is made to the OPO, the Referral Coordinator at the OPO appoints a Family Care Coordinator (FCC) to the case, who is responsible for following up with the hospital regarding the health condition of the potential donor and attending to the needs of the potential donor’s family members facing the stressful situation. For hospitals that are not immediately accessible by an FCC, OPOs typically conduct training sessions for the hospital staff on how to approach the matter of donation with the potential donor’s family. Based on the health condition of the patient, the FCC may call in the Transplant Coordinator, who is on the OPO staff and is a trained emergency room and transplant specialist, to get involved in the care of the patient. If the condition of the potential donor shows no improvement, hospital doctors proceed to perform the Brain Death (BD) test on the patient. After declaration of BD, the Transplant Coordinator takes steps to stabilize the patient in order to keep the organs viable for recovery. Once the nearest-of-kin of the deceased gives written authorization for organ donation (typically referred to as family authorization), the OPO proceeds to find matches for the donor organs in the waitlist. The OPO pays the hospital the costs of all medical procedures and tests performed after family authorization is received.

3.3. The OPO–Hospital Relationship

The relationship between the non-profit OPO and hospitals in its DSA is a critical component of an ODVC. Both entities are vital to the OPTN as they both constitute the supply side of an ODVC. However, organ donation activities suffer due to a lack of coordination between these two essential ODVC partners. Several consensus reports, including that of the National Center for Biotechnology Information (2002) have lamented the suboptimal organ donation conversion rate. Nearly two-thirds of HCPs surveyed by Traino et al. (2012) considered OPO staff to be “outsiders.” Goodman et al. (2003) highlighted areas of improvement and suggested best practices to ensure that OPOs and hospitals work in
tandem, including the need for better coordination between OPOs and hospitals to ensure early participation of OPOs in the family authorization seeking process, and the value of establishing organ donation committees comprising OPO staff and hospital staff.

OPOs typically audit patient records of their DSA hospitals at regular intervals (monthly or quarterly) to collect data on missed opportunities for organ donation. Any missed opportunity or a referral made after pronouncement of BD is termed as a “missed referral”. This data is used by the OPOs to provide feedback to hospital staff and to provide additional training to help them identify and refer potential donors in the future. OPOs typically do not report this data to the CMS either at the hospital level or at an aggregate OPO level because OPOs do not want to negatively impact their relationships with hospitals (Brown 2000). Although OPOs and hospitals typically sign agreements to coordinate the procurement and use of anatomical gifts as per CMS ruling 42 CFR §1320b-8(a) (in order for hospitals to be able to participate in Medicare and Medicaid programs), OPOs currently have very limited ways of inducing organ recovery efforts at hospitals.

Interviews with OPO officials consistently revealed the observation that organ recovery is not accorded sufficient priority by the hospitals in the scheduling of ORs, where organ recovery and other inpatient procedures take place. However, Ranjan et al. (2006) conducted a retrospective financial analysis of potential donor management at a Medicare-approved transplant hospital and showed that organ donation for Medicare-approved transplant hospitals can in fact be financially attractive for those hospitals. OPOs typically reimburse hospitals in a timely manner and at Medicare-prevailing rates, which are typically higher than third-party insurance company rates. Thus, the timely and financially attractive reimbursements are at odds with the observation of low or insufficient priority for organ recovery by hospitals. However, in their analysis, Ranjan et al. (2006) only include the direct costs of maintaining a potential donor and do not take into account indirect costs (e.g. opportunity cost of OR utilization and disutility associated with inpatient waiting).
Thus, the preceding discussion underscores the importance of a strong relationship between the two supply-side ODVC players – the OPO and the hospital where potential donors arrive – in the form of relevant efforts, timely referrals, and timely organ recovery; yet interactions among the contextual parameters and decisions of these players have not been well-studied. We address this critical gap with our analysis from the perspective of the social planner, which incorporates operational actions for organ recovery, interactions between the OPO and hospital, and individual and societal objectives.

4. Model

Based on the organ donation process and the sequence of multiple interactions between the OPO and the hospital, we develop an analytical model to represent the current scenario and then, through our analysis, propose contractual mechanisms to improve the societal outcome of the ODVC. We assume the arrival of medically suitable potential donors who meet the criteria for imminent death to be a Poisson process with arrival rate $\lambda_p$. For tractability, we consider a homogenous pool of incoming potential donors and restrict our analysis to one focal organ. We model the interaction between the hospital and OPO within an ODVC as a Stackelberg game. The hospital, because of its say in the referral of potential donors to the OPO and in OR scheduling, is the Stackelberg leader. The hospital makes two operational decisions. **First**, the hospital decides its level of effort ($\xi_h$) to commit to organ recovery activities; specifically, personnel training and time involved in identifying and referring potential donors. We normalize the hospital’s effort level such that $\xi_h \in [0, 1]$ and assume that the fraction of the arrivals of potential donors who end up as “referred” donors (denoted by $f_h$) is increasing in the hospital’s effort $\xi_h$, such that $f_h = \tau \xi_h$, where $\tau (0 < \tau \leq 1)$ captures the hospital’s affinity (exogenous) to organ donation activities.

Several studies reveal that HCPs find it difficult to broach and discuss the subject of organ donation with the family of the potential donor. Also, participating in the process of organ
procurement is only one aspect of their jobs. Chernenko et al. (2005) estimated that 77% of registered nurses and 44% of doctors found it difficult to communicate and explain the concept of brain death to families. Training-related reasons for HCPs not referring potential donors include lack of knowledge regarding the concept of brain death, lack of knowledge as to how to refer potential organ donors, and lack of knowledge about organ transplantation outcomes for recipients (Molzahn et al. 2003).

Siminoff et al. (2009) conducted an event study to show that training of OPO coordinators (such as FCCs), who are responsible for seeking family authorization for organ donation, was associated with an increase in the likelihood of authorization. Another study found that 20.3% of families that initially refused donation and 65.8% of families who were undecided at first, eventually consented when reapproached (Frutos et al. 2002). Thus, through interactions with the potential donor’s family members, the OPO’s effort level ($\xi_o$) influences the fraction of referred donors who are “authorized” for organ donation. We denote the fraction of referred donors (i.e., donors referred by the hospital to the OPO) who end up as authorized donors (i.e., donors whose families consent to organ recovery) by $f_o$ and assume $f_o = \theta \xi_o$, where $\xi_o \in [0,1]$. $\theta$ ($0 < \theta \leq 1$) captures donors’ or their families’ affinities towards organ donation irrespective of the OPO’s effort. For exposition and without loss of generality, we normalize $\theta$ to 1. Thus, the rate of authorized donors from whom organs are recovered, is $\lambda_a = f \lambda_p$, where $f = f_h f_o = \tau \xi_h \xi_o$ (see Figure 1).

For simplicity, we assume that potential organ recipients are identified from the central UNOS database immediately after a potential donor becomes an authorized donor. In
other words, no time is lost in identifying potential recipients. Also, we assume that the flows in Figure 1 are such that we can use the Partition Theorem for Poisson Processes (see Appendix B).

Second, the hospital schedules organ recovery and other inpatient procedures in its OR. The OR is most often a hospital’s bottleneck because of the expensive medical equipment and specially trained staff that are typically required (Hall 2006). In a study describing critical issues and opportunities for researchers in healthcare operations, Green (2012) underscores the need for improved capacity management of specialized units. Optimal utilization of ORs is critical to cost and quality outcomes because they are the costliest units in the hospital and they serve among the most sick and complex patients. At this stage, the hospital has to ration scarce critical care resources between the care and treatment of living patients requiring these facilities, and the recovery of organs from deceased donors.

We model the OR of the hospital as an M/G/1/[2] queue system. The two classes of patients competing for OR resources are: authorized cadaveric donors (a), and other hospital patients (h) that need to access the OR, with Poisson arrival rates \( \lambda_a \) and \( \lambda_h \) respectively. We consider two OR priority cases (denoted by \( \chi \)): \( \chi = I \), where the hospital prioritizes authorized donors over other hospital patients, and \( \chi = II \) being the opposite. Patients in each class require a random amount of time in OR care, with mean \( \frac{1}{\mu_x} \) and second moment \( \nu_x \), where \( x \in \{a, h\} \). Denote \( \rho_x = \frac{\lambda_x}{\mu_x} \). Let, \( w_a \) and \( w_h \) denote the average wait times in queue for the patients of each class. We assume \( \rho_a < 1 \), \( \rho_h < 1 \), \( \rho_a + \rho_h < 1 \), non-preemptive priority (i.e. the patient under consideration is processed completely before the next patient) and first-come first-serve policy within each of the two classes of arrivals. Further, we restrict our analysis to parameter settings where all constraints on the model’s variables and decisions are met. Based on our interviews with ODVC members, including with a trauma care manager at a medium-sized multi-speciality hospital, we assume that
the arrival rate of potential donors is relatively low compared to their service rate in the OR. Thus,

**Assumption 1.** The arrival rate of potential donors is relatively very low compared to their service rate in the OR i.e. \( \lambda \ll \mu_a \). (A1)

### 4.1. OPO and Hospital Objectives

As mentioned before, OPOs are not-profit organizations with a volume-of-care objective, i.e., saving as many lives as possible by effectively managing organ donation activities in their DSAs. A survey of mission statements of various OPOs, including Lifelink of Georgia, Carolina Donor Services, Nevada Donor Network, Gift of Life Michigan, and Living Legacy Foundation of Maryland, indicates that OPOs focus on maximizing the number of organ donors in their respective DSAs. As discussed earlier, OPOs have to meet the volume-based standards set by CMS in order to maintain their Medicare certification. Thus, the objective of the OPO is to maximize \( \pi_{opo} := \lambda_a \), the rate of authorized donors. We denote the optimal effort level for the OPO, i.e., the effort level that maximizes \( \pi_{opo} \) as \( \xi_o^* \).

Once a suitable match is found for an organ, the OPO assumes responsibility for arranging a team – comprising OPO surgeons and specially trained nurses – for organ recovery surgery. For its services related to caring for and managing authorized donors, the hospital receives a reimbursement amount irrespective of organ recovery outcomes (e.g., if the organ is deemed to be unviable by the recipient’s transplant surgeon; CMS Ruling No. CMS-1543-R). This amount consists of two components: a fixed reimbursement rate per authorized donor (denoted by \( R_{af} \)) that includes laboratory test charges, medical equipment use charges, and anesthesiology consultation fees, and a variable reimbursement rate per authorized donor per unit care time (denoted by \( R_{av} \)), which depends on the waiting time \( (w_a) \) of the authorized donors in the ICU before organ recovery surgery in the OR.

We denote the average per-patient reimbursement rate associated with the hospital’s other patients by \( R_h \). We denote \( C_h \) as the net cost to the hospital in the form of customer
dissatisfaction and reputation loss arising from inpatient waiting \( (w_h) \); we assume that \( C_h \) subsumes the variable reimbursement rate (per patient per unit time) applicable to the care time of the hospital’s other patients. As in Green et al. (2006) and Hall (2006), we assume \( C_h \) to be linear in \( w_h \), i.e., of the form \( C_h = c_h w_h \). The emotional stresses and discomfort involved in dealing with the difficult subject of organ donation adds further disutility, resulting in a non-linear relationship such that the hospital’s cost of effort \( C_\xi \) is convex increasing in \( \xi_h \); we assume \( C_\xi = \frac{c_\xi \xi^2_h}{2} \). Thus, the hospital’s payoff (average profit rate) is:

\[
\pi_h = \lambda_a R_{af} + \lambda_a R_{as} w_a + \lambda_h R_h - C_h - C_\xi. \tag{1}
\]

4.2. Social Planner’s Objective

Delays in the organ recovery process have a negative influence on the quality of the recovered organ (Cantin et al. 2003). Prolonged waiting for the OR after declaration of BD can lead to an organ deemed unusable by the transplant surgeon because of an increased likelihood of organ failure post-transplantation and rejection of the transplanted organ by the recipient’s body (Kunzendorf et al. 2002, Van Der Hoeven et al. 2003). From a socio-economic standpoint, the quality of the recovered organ is an important parameter that determines graft survival as well as the quality of life of the recipient post-transplantation (Howard 2002). Further, Medicare covers dialysis costs, medication costs, and hospitalization costs for any patient suffering from end-stage renal disease (ESRD). Medicare expenditures for ESRD have been on the rise; these expenditures rose by 8.0% in 2010, 6.8% in 2011 and 5.4% in 2012 (USRDS 2013). As stated earlier, average Medicare cost savings per kidney transplant are of the order of $40,000 per year post-transplantation, for the life of the recipient. Also, Winkelmayer et al. (2002) show that benefits to Medicare of kidney transplantation substantially exceed the cost of dialysis for ESRD patients.

We represent the social planner’s objective in terms of the monetary value of quality-adjusted life years (QALYs) added. Introduced by Klarman and Rosenthal (1968), QALY
was developed as a way to combine the length of life and quality of life into a single measure. The US Panel on Cost-Effectiveness in Health and Medicine recommends that QALY be used as the principal measure of health outcomes (Siegel et al. 1996). We assume the monetary value of QALYs added to an organ recipient to be of the form $Q_a(1 - q_aw_a)$, whereby the value is a decreasing function of the delay ($w_a$) experienced by the organ, with an upper limit on the delay beyond which the increment in QALY is negligible (in the relationship, $\frac{1}{q_a}$ captures this upper limit). Similarly, we assume the monetary value of QALYs added to the hospital’s other patients that access the OR to be of the form $Q_h(1 - q_hw_h)$, where $w_h$ is the average delay experienced by them while waiting for the OR to become available.

**Assumption 2.** $Q_a \gg Q_h$. (A2)

A2 finds support in the medical literature surveyed in the Cost–Effectiveness Analysis Registry (CEAR Database), which is maintained by the Center for the Evaluation of Value and Risk in Health. For instance, the value per QALY for an average organ transplant is more than $100,000, whereas that for other hospital OR procedures include: hip arthroplasty, $2300 to $4800/QALY; knee arthroplasty, $6500 to $12,700/QALY; and carpal tunnel surgery, $140 to $280/QALY. Also, in terms of QALY gains (on average, over the recipient’s lifetime), lung transplants add about 11 QALYs and heart transplants add about 6.8 QALYs to the recipient, as compared to about 0.8 QALYs added by hip arthroplasty and 0.66 QALYs added by bypass surgery. The social planner’s payoff (rate), normalized by the parameter $Q_a$, is:

$$\pi_S = \lambda_h \frac{Q_h}{Q_a} (1 - q_hw_h) + \lambda_a (1 - q_aw_a)$$  \hspace{1cm} (2)

5. **Analysis**

We first present the optimal operational actions of hospital and OPO in the current scenario and discuss their divergence from socially-optimal actions. Thereafter, we discuss the design of socially optimal contracts between the social planner, and the OPO and the hospital.
We use the results from Gelenbe and Mitrani (1980), related to the average wait times in queue in a multiclass queueing system, to obtain expressions for \( w_a \) and \( w_h \) – the average wait times in the OR queue for authorized donors and the hospital’s other patients:

For \( \chi = I \) (priority to authorized donors) we have: 
\[
w_a = \frac{(\lambda_a \nu_a + \lambda_h \nu_h)}{2(1 - \rho_a)}, \quad w_h = \frac{(\lambda_a \nu_a + \lambda_h \nu_h)}{2(1 - \rho_a - \rho_h)}
\]
and, for \( \chi = II \) (priority to the hospital’s other patients) we have: 
\[
w_h = \frac{(\lambda_a \nu_a + \lambda_h \nu_h)}{2(1 - \rho_h)}, \quad w_a = \frac{(\lambda_a \nu_a + \lambda_h \nu_h)}{2(1 - \rho_h)(1 - \rho_a - \rho_h)}.
\]

Under assumption A1, \( w_a \) and \( w_h \) are linear increasing in the fraction \( f \) of potential donors that end up as authorized donors, under both OR priority schemes. Because \( f \) increases in \( \xi_h \) and \( \xi_o \), a consequence of increased effort by either the hospital or the OPO is greater OR congestion, leading to longer wait times for both classes of patients.

5.1. Current (Uncoordinated) Scenario: OPO and Hospital Actions

Recall that the OPO is the Stackelberg follower, with the non-profit objective of maximizing volume of care. It is therefore intuitive (as indicated in Proposition 1) that the OPO will always exert its highest effort level in order to increase the rate of authorized donors.

**Proposition 1.** For any given model parameters, \( \xi_o^* = 1 \).

Note that the OPO’s optimal choice of effort is independent of the OR priority scheme chosen by the hospital. However, it is optimal for the hospital to accord priority to its other patients because a higher priority to organ donors results in: (i) Lower wait times for authorized donors (leading to lower revenue from the variable component \( R_{av} \) in the hospital’s payoff in (1)), (ii) Higher wait times for the hospital’s other patients (resulting in a higher net cost to the hospital \( C_h \)). Thus, \( \chi_h^* = II \). Proposition 2 characterizes the hospital’s effort level \( \xi_h^* \) that maximizes its private objective in the current scenario. Denote 
\[
\pi_h^* = \pi_h(\xi_h^*, \chi_h^*).
\]

Let: 
\[
(i) \quad A = R_{av} \frac{\lambda^2 \nu_a^2}{1 - \rho_h} - \frac{c_h}{\tau}, \quad (ii) \quad B = [R_{af} + R_{av} \frac{\lambda_a \nu_a}{2(1 - \rho_a)} - c_h \frac{\nu_a}{2(1 - \rho_h)}] \tau \lambda_p.
\]

A captures the component of the hospital’s payoff that is quadratic in its effort level \( \xi_h \) and \( B \) captures the component that is linear in \( \xi_h \).
Proposition 2. The following four cases characterize the hospital’s optimal effort level $\xi_h^*$:

(i) $A < 0$ and $B \leq 0$: $\pi_h$ is concave decreasing in $\xi_h$, i.e., $\xi_h^* = 0$;
(ii) $A < 0 < B$: $\pi_h$ is concave in $\xi_h$ (either unimodal or increasing), i.e., $0 < \xi_h^* \leq 1$;
(iii) $A > 0$ and $B \geq 0$: $\pi_h$ is convex increasing in $\xi_h$, i.e., $\xi_h^* = 1$;
(iv) $B < 0 < A$: $\pi_h$ is convex in $\xi_h$ (unimodal), i.e., $\xi_h^* = 0$ or 1.

To maximize its objective of volume of care, it is in the OPO’s private interest for the hospital to exert the highest effort level. However, Proposition 2 points out several instances where the private incentives of the OPO and the hospital are misaligned. In the previous sections, we have already highlighted the adverse effects of a strained OPO–hospital relationship on ODVC performance. Let $\tilde{f}$ denote the equilibrium fraction of potential donors that end up as authorized donors in the current scenario, i.e. $\tilde{f} = \tau \xi_h^* \xi_o^*$. Let $\Theta_1$ denote the set of parameter conditions such that $\xi_h^* = 1$, and let $\Theta_2$ denote the set of parameter conditions such that $\xi_h^* < 1$. For instance, a sufficiently low $R_{av}$ and a sufficiently high $R_{af}$ in the hospital’s payoff in (1) would lead to $\xi_h^* = \frac{B - A}{A} < 1$.

5.2. Centralized Scenario: Socially Optimal Actions

The operational actions of the OPO and the hospital – their respective effort levels and OR priority – affect the delay (i.e., $w_a$) experienced by the organ and, thus, the social planner’s payoff $\pi_S$. Under assumption A2, the social planner’s payoff can be expanded as: $\pi_S(f, \chi) \cong f \lambda_p [1 - q_a w_a(f, \chi)]$. It can be shown, using the relation $w_a(f, \chi = II) > w_a(f, \chi = I)$, that the social planner is always better off if the hospital gives higher OR priority to authorized organ donors over its other patients, i.e., $\chi_S^* = I$. Proposition 3 provides the socially-optimal fraction of potential donors that should end up as authorized donors.

Proposition 3. Under assumptions A1 and A2, and with a higher OR priority for authorized donors over the hospital’s other patients, the social planner’s objective is concave
in the fraction \( f \) of potential donors that end up as authorized donors. The socially-optimal fraction is given by 

\[
\tilde{f}^* = \frac{1 - q_a \frac{\lambda_h \nu_h}{q_a \lambda_p \nu_a}}{q_a \lambda_p \nu_a}.
\]

We denote \( \pi^*_S = \pi_S(f^*_S, \chi^*_S) \). Note that, for a given OR priority, the social planner’s payoff depends only on the effective fraction \( f = f_h f_o \) of potential donors that end up as authorized donors and not the individual values of \( f_h \) and \( f_o \) per se (see Figure 1).

Consider the following two cases: (i) \( \tilde{f} > f^*_S \): For example, a sufficiently large \( q_a \) would lead to this relationship (recall that \( q_a \) is the sensitivity of QALYs added to the organ recipient to the delay experienced by the organ while waiting for the OR to become available). In this case, the social planner would like the hospital and/or the OPO to exert lower effort than the equilibrium levels due to the adverse effect on OR congestion and, hence, on QALY. However, this would conflict with the OPO’s volume-of-care objective, and possibly the hospital’s profit objective. (ii) \( \tilde{f} < f^*_S \): For example, a sufficiently low \( q_a \) would lead to this relationship. In this case, because the OPO already exerts its highest effort level, the social planner would want the hospital to exert greater effort in order to further increase \( \lambda_a \), although this would increase congestion at the OR and would not be privately optimal for the hospital.

The problem at hand can be viewed as a principal-agent problem, wherein contracts need to be designed if the social planner (principal) intends for the hospital and the OPO (agents) to make operational decisions that would lead to the same payoff to the social planner as would be the case if the social planner were able to specify the effort level required of the OPO, and the effort level and OR priority required of the hospital. Although OPOs are responsible for day-to-day OPTN operations, given the structure of the network, they do not have direct control over several crucial tasks involved in organ recovery activities at the hospital level, for instance, the timely reporting of imminent deaths by hospital staff, efforts from the nursing staff in maintaining the BD patient, and scheduling organ recovery
surgery. It is interesting to note that a mismatch in the objectives of the social planner and hospital exists even if the hospital gives higher OR priority to organ recovery. Clearly, the degree of misalignment of the OPO’s, hospital’s, and social planner’s objectives depends upon parameter conditions. Depending on these conditions, socially-optimal contracts can be designed that either: (a) directly specify the OPO’s level of effort, and the hospital’s level of effort and OR priority for organ recovery, or (b) penalize/alter the objective the OPO and/or the hospital to induce desired organ recovery outcomes. Being administratively simpler, and because OPOs operate under a federal mandate and typically collect data on missed referrals by hospitals, we focus on the latter.

5.3. Socially Optimal Contracts

We propose a multiparameter contract to address the misalignment between the social planner’s objective and the non-profit OPO’s and for-profit hospital’s objective. First, we suggest adding a QALY-based component to the existing volume-based objective of the OPO, thus making the OPO’s objective based on composite criteria. This additional component would help alleviate the conflict between the non-profit, volume-of-care objective of the OPO and the adverse effect of this volume ($\lambda_a$) on OR congestion and, hence, on QALY outcomes. Let $\alpha > 0$ and $\beta > 0$ denote respective weights of the QALY-based and volume-based components in the revised objective of the OPO, i.e., $\hat{\pi}_{opo} = \alpha \pi_S + \beta \pi_{opo}$. Let $\hat{\xi}_{o}^*$ denote the value of the OPO’s effort that maximizes $\hat{\pi}_{opo}$, under the contract.

In practice, hospitals do not bear any financial penalty for adverse ODVC performance outcomes, except for a verbal slap on the wrist for choosing suboptimal effort levels (see the DHHS report by Inspector General Brown (2000)). Although the aforementioned DHHS report recommends that some kind of penalty be used to increase hospital’s efforts towards organ recovery activities, to our knowledge no such penalty scheme exists in practice. Almost all OPOs already collect data on late and missed referrals, so there would be limited additional administration costs for implementing penalties based on missed referrals.
Moreover, this contract design is in line with a similar penalty (Readmission Penalty Policy) introduced by the CMS in October 2012 to curb the substantial costs incurred due to avoidable rehospitalizations of Medicare beneficiaries (CMS 2015). We suggest a contract such that the social planner levies a penalty (at a rate \( p \)) on the hospital for each missed referral (i.e., a penalty proportional to \( 1 - \xi_h \)). With this penalty, the payoff function of the hospital can be re-written as:

\[
\hat{\pi}_h = \lambda_aR_{af} + \lambda_aR_{aw}w_a + \lambda_hR_h - c_hw_h - \frac{\xi \xi^2}{\tau} - \lambda_p p(1 - \xi_h)
\]  

We denote the hospital’s optimal effort level and OR priority in the presence of the penalty for missed referrals by \( \hat{\xi}^*_h \) and \( \hat{\chi}^*_h \) respectively. Denote \( \hat{\pi}^*_h = \hat{\pi}_h(\hat{\xi}^*_h, \hat{\chi}^*_h) \).

The set of contractual levers \( \{\alpha, \beta, p\} \) outlined above can help the ODVC attain the socially optimal payoff \( \pi^*_S \) (in §5.2) and, when properly specified, can even help achieve Pareto improvement. In our context, Pareto improvement implies that none of the three entities, namely, the OPO, the hospital, or the social planner is worse-off, and at least one of them is strictly better-off. For the hospital and the social planner, strictly better-off would imply that their respective payoffs attain larger values as compared to the current (uncoordinated) scenario whereas, for the OPO, strictly better-off would mean that its optimal effort level is less than 1. For the non-profit OPO, any amount of effort saved can be utilized towards fundraising activities, public awareness campaigns, community engagement programs, and relationship-building exercises with hospitals. This is a desirable situation because OPOs operate in resource-constrained environments (both monetary and personnel, Shafer et al. (2003)).

We focus on Pareto-improving contracts for their greater promise of acceptability. The suggested contractual levers in Proposition 4 not only align the operational actions of the hospital and the OPO with the socially optimal levels, but also achieve Pareto improvement.
Proposition 4. \( \exists p_o \) s.t. \( \forall \beta > 0 \) and \( \forall p \geq p_o \) the set of contractual levers \( \{ \hat{\alpha} = \beta(\frac{1-p_h}{p_h}), \beta, p \} \) ensures: (i) Social optimality, i.e., \( \hat{\pi}_S(\hat{\alpha}, \beta, p) = \pi^*_S \) and, (ii) Pareto improvement, i.e., \( \hat{\xi}^*_o < 1 \) and \( \hat{\pi}^*_h \geq \pi^*_h \), or, \( \hat{\xi}^*_o \leq 1 \) and \( \hat{\pi}^*_h > \pi^*_h \).

As stated in §5.1 (current, uncoordinated scenario), the OPO’s choice of effort is independent of the hospital’s chosen OR priority scheme. However, the social planner and the hospital have opposing optimal OR priority schemes (\( \chi^*_S = I \) and \( \chi^*_h = II \)). Under the revised objective function for the OPO, choosing \( \alpha \) and \( \beta \) s.t. \( \frac{\alpha}{\beta} = \frac{1-p_h}{p_h} \) ensures that the optimal payoff (\( \pi^*_S \)) of the social planner is achieved even if the hospital does not prioritize authorized organ donors. Recall that the OPO is the Stackelberg follower; an appropriately chosen weight for the QALY-based component in the OPO’s objective function ensures that the OPO adjusts its effort in response to the hospital’s chosen effort level, thereby balancing the volume-of-care and QALY outcomes. The social planner can always choose a value of \( p \) such that \( \hat{\xi}^*_o < 1 \), so that the OPO is strictly better-off under the contractual mechanism in Proposition 4 as compared to the current scenario.

Setting \( \alpha \) and \( \beta \) as per Proposition 4, effectively fixes the fraction (\( f \)) of potential donors converted to authorized donors. Note that if the penalty for missed referrals, \( p = 0 \), at a fixed level of \( f \), the hospital’s payoff is convex decreasing in \( \xi_h \) (i.e., it is not optimal for the hospital to exert effort). By levying a non-zero penalty on the hospital for missed referrals, the social planner induces an interesting dynamic between the OPO and the hospital. In the presence of a non-zero penalty for missed referrals, it becomes costly for the hospital to not exert effort. However, because of the presence of the QALY-based component in the OPO’s revised objective, the OPO (Stackelberg follower) responds by substantially reducing its effort level. This can end up benefiting the hospital because of decreased OR congestion and, hence, decreased disutility from inpatient waiting.
6. Conclusion

Our analysis reveals several key findings. First, we show that although a higher effort level chosen by both the hospital and the OPO leads to a larger fraction of conversions of potential donors to authorized donors, it also leads to greater congestion at the OR, leading to higher wait times for both classes of OR arrivals – authorized donors and other hospital patients. The increased wait time in the OR queue for authorized donors adversely impacts QALY outcomes.

Second, we show that the social planner’s objective is non-monotonic in the fraction of conversions of potential donors to authorized donors. In other words, from the social planner’s perspective, it is not always desirable for the OPO and/or the hospital to exert significant amounts of effort. Based on the first author’s participation in one of the quarterly meetings of the Donor Advisory Committee of a medium-sized hospital, which included liaison officers from the OPO, and trauma-care program managers, doctors, nurses and, transplant surgeons from the hospital, we suggest that the effort levels may be agreed upon in such joint meetings between OPO and hospital staff.

Third, we illustrate the effects of specific contextual parameters on the payoffs of the non-profit OPO, the for-profit hospital and the social planner. The parameter conditions, in turn, determine the degree of incentive misalignment. We recommend a multiparameter contract to address the misalignment between the social planner’s objective and the OPO’s and hospital’s objectives. We show that by adding a QALY-based component to the existing volume-based objective of the OPO (i.e., extending the OPO’s objective to reflect composite criteria), and by levying a penalty on the hospital for missed referrals, the social planner can not only align the operational actions of the hospital and the OPO to help the ODVC achieve socially-optimal performance, but also achieve Pareto improvement. We believe that our recommended contractual mechanism is administratively feasible (since
OPOs operate under a federal mandate and already collect data on missed referrals by hospitals) with greater promise of acceptability (since no player is worse off).

The coordination challenges on the supply side of the ODVC mirror those discussed in the literature on non-profit operations, namely, the divergence between the objectives targeted by profit and non-profit organizations, and the resulting incentive misalignment and lack of inter-organizational collaboration. By showing the existence of a Pareto-improving mechanism in our context, we illustrate the possibility for social value for the non-profit participants to not necessarily be at the expense of economic value for the for-profit participants. Another important consequence of the contractual mechanism discussed above is that the socially-optimal level of OPO’s effort can be strictly less than its maximum possible effort level. Thus, under our recommended contractual mechanism, it is possible for an OPO to be able to commit a larger portion of its available capacity to accomplish other important tasks, e.g. fundraising and improving public awareness about the merits of organ donation. Also, the OPO may be able to assist the hospital staff in lowering their discomfort associated with organ donation activities and share HCP training responsibilities in order to improve the hospital’s affinity towards organ donation.

Apart from contractual levers, our model suggests other potentially viable operational interventions for improving organ recovery outcomes: expanding OR capacity (higher $\mu$), improving the waiting experience in the OR queue (lower $C_h$), and emphasizing training to reduce the hospital staff’s discomfort associated with organ donation activities (lower $C_\xi$).

**Limitations and Future Research**

Our model assumes a homogenous pool of potential donors and focuses on one organ type. In practice, potential donors could vary in organ quality. Also, a cadaveric donor can potentially donate multiple organs. It will be interesting to study the socially- and
privately-optimal levels and allocations of efforts by the OPO and the hospital as well as the relative OR priorities accorded by the hospital to multiple patient classes in the presence of heterogeneity in donor and organ characteristics (for instance, the sensitivity of organ quality to delays depending on donor or organ type).

Finally, as discussed earlier, the existing OM literature focuses on the demand side of ODVCs whereas our paper adds to the sparse literature on the supply side. We believe that there will be value to capturing the interplay between demand- and supply-side actions in order to further improve societal outcomes. For instance, it will be valuable to study the impact of operational actions in the organ recovery process on the trade-offs involved in the dynamic allocation of organs to patients on the waitlist.

Appendix A: Example of a Trigger Card issued by an OPO

Appendix B: Partition Theorem for Poisson Processes

If $N \sim \text{Poisson} (\lambda)$ and if each arrival of $N$ is, independently, type 1 or type 2 with probabilities $j$ and $k$, respectively ($j + k = 1$) then, letting $N_i$ denote the point process of type $i$ arrivals, where $i \in \{1, 2\}$, the two resulting point processes are themselves Poisson and independent: $N_1 \sim \text{Poisson} (j\lambda)$, $N_2 \sim \text{Poisson} (k\lambda)$, and independent.
Appendix C: Proofs of Propositions

Let $w_x^\chi$ denote the average wait time in OR queue for each OR patient class, $x \in \{a, b\}$ and priority $\chi \in \{I, II\}$.

PROOF OF PROPOSITION 1. $\frac{\partial \pi_n}{\partial \xi_h} = \tau \xi_h \lambda_p \geq 0 \Rightarrow \xi_h^* = 1$ always.

PROOF OF PROPOSITION 2. Under A1, $w_h^I \equiv w_h^{II}$. Thus, it is straightforward to show that $\chi_h^* = II$.

Substituting the expression for $w_h^{II}$ in place of $w_a$ and $f = \tau \xi_h \chi_a = \tau \xi_h$ in (1), we obtain:

$$\frac{\partial \pi_h}{\partial \xi_h} = [R_a + R_\nu \frac{\lambda_h \nu_h}{2(1 - \rho_h)} - c_h \frac{\nu_a}{2(1 - \rho_h)} - \frac{c_h}{2}] \tau \lambda_p + \xi_h[R_\nu \frac{\lambda_h^2 \nu_h \tau^2}{1 - \rho_h} - \frac{c_h}{\tau}] = B + \xi_h A$$

When $A < 0$, $\pi_h$ is concave, otherwise it is convex (because $\frac{\partial^2 \pi_h}{\partial \xi_h^2} = A$). Therefore, the hospital’s objective and optimal effort level ($\xi_h^*$) can be categorized by the following four cases: (i) $A < 0$ and $B < 0 \Rightarrow \frac{\partial \pi_h}{\partial \xi_h} < 0 \Rightarrow \pi_h$ is concave decreasing and $\xi_h^* = 0$. (ii) $A < 0$ and $B \geq 0 \Rightarrow \frac{\partial \pi_h}{\partial \xi_h} \geq 0 \Rightarrow \pi_h$ is concave increasing and $\xi_h^* = 1$. (b) $A + B < 0 \Rightarrow \pi_h$ is concave (unimodal) and $\xi_h^* = \frac{\partial \pi_h}{\partial \xi_h} = \frac{B}{A} < 1$. (iii) $A > 0$ and $B \geq 0 \Rightarrow \frac{\partial \pi_h}{\partial \xi_h} > 0 \Rightarrow \pi_h$ is convex increasing and $\xi_h^* = 1$. (iv) $B < 0 < A \Rightarrow \pi_h$ is convex (unimodal) and, (a) $\frac{B}{A} + \frac{c_h \nu_h}{2(1 - \rho_h)} + B \geq 0 \Rightarrow \xi_h^* = 1$. (b) $\frac{B}{A} + \frac{c_h \nu_h}{2(1 - \rho_h)} + B < 0 \Rightarrow \xi_h^* = 0$. The two sub-cases in Case (iv) arise from comparing $\pi_h\vert_{\xi_h=1}$ and $\pi_h\vert_{\xi_h=0}$.

Restricting our focus to the cases where $\xi_h^* > 0$, we can say that $\xi_h^*$ is either equal to 1 (under $\Theta_1$) or $\frac{B}{A}$ (under $\Theta_2$).

PROOF OF PROPOSITION 3. $\pi_S$ decreases in $w_a$; $w_a(\chi = II) > w_a(\chi = I) \Rightarrow \chi_S^* = I$. Substituting the expression for $w_h^I$ in place of $w_a$, we get (under A2): $\frac{\partial \pi_S}{\partial f} \equiv \lambda_p(1 - f g_a \lambda_p \nu_a - g_a \lambda_p \nu_a)$. Since $\frac{\partial^2 \pi_S}{\partial f^2} < 0$, equating $\frac{\partial \pi_S}{\partial f}$ to 0 yields $f_S^* = \frac{1 - g_a \lambda_p \nu_a}{g_a \lambda_p \nu_a} \lambda_p$.

PROOF OF PROPOSITION 4. It is optimal for the hospital to set $\hat{\chi}_h^* = II$. Substituting $w_h^{II}$ for $w_a$ in $\hat{\pi}_{opo}$, we have $\frac{\partial^2 \hat{\pi}_{opo}}{\partial \hat{\pi}_h^2} < 0 \Rightarrow \hat{\pi}_{opo}$ is maximized at $\hat{f} = \frac{\lambda_p \nu_a}{g_a \lambda_p \nu_a} \lambda_p$. It follows that, $\forall \beta > 0$, choosing $\hat{\alpha}$ s.t.

$$\hat{f} = \frac{1 - \alpha \nu_h}{1 - \rho_h} \frac{\lambda_h \nu_h}{\nu_h} \lambda_p$$

ensures that $\hat{\pi}_S(\hat{\alpha}, \beta, p) = \pi_S^*$.

Under the given contractual mechanism, $\frac{\partial \hat{\pi}_h}{\partial \xi_h} = -\frac{2}{\xi_h^*} \xi_h + p \lambda_p$. Since $\frac{\partial^2 \hat{\pi}_h}{\partial \xi_h^2} = -\frac{2}{\xi_h^*} < 0 \Rightarrow \hat{\pi}_h$ is maximized at $\hat{\xi}_h^* = \frac{p \lambda_p}{\xi_h^*}$. Substituting the values of $\hat{\xi}_h^*$ and $\xi_h^*$ in (3) and (1), respectively, we specify the conditions that ensure $\hat{\pi}_h^* - \pi_h^* \geq 0$ in the following two cases:

(i) $\hat{f} < f_S^*$: It is sufficient to show the following in order to ensure $\hat{\pi}_h^* - \pi_h^* \geq 0$.

$$f_h^\alpha \lambda_p \nu_a \frac{\tau}{c_h} + \frac{\tau A^2}{2} \left(1 - \frac{p \tau \lambda_p}{c_h} \right) \leq \frac{\tau A^2}{2} \left(1 - \frac{p \tau \lambda_p}{c_h} \right) \left(1 - \frac{p \tau \lambda_p}{c_h} \right) \leq \frac{B^2}{2 \tau A^2}$$

The above inequality can be rewritten as $ap^2 + bp + c \geq 0$, where $a = \lambda_p^2$, $b = -2 \frac{c_h \lambda_p}{c_h}$, and $c = \frac{c_h^2}{4} - \frac{c_h \lambda_p}{c_h} (f_h^\alpha - \tau A^2) \lambda_p^2$. The discriminant of this quadratic equation is always $\geq 0$. This implies that there
exist two real roots. Since, $b < 0$, the sum of the two roots $= -\frac{b}{a} = \frac{-b}{\lambda_p^2}$ is $> 0$, which shows that there exists at least one root (say, $p_1$) that is $> 0$. $\Rightarrow ap^2 + bp + c \geq 0 \forall p \geq p_1$.

(ii) $\tilde{f} > f^*_S$: In this case, the necessary and sufficient condition to ensure $\pi^*_h - \pi^*_o \geq 0$ can be written as $qp^2 + rp + s \geq 0$, where $q = \lambda_p^2$, $r = -2\frac{c\gamma_a}{\beta}$, $s = -\frac{\gamma_a^2}{\lambda^2} \lambda^2 (\Delta R) + 2\frac{\gamma_a}{\lambda^2} \frac{\beta}{\lambda \mu} (\frac{\gamma_c}{\beta} - f^*_S) \lambda^2 p_2 + \frac{\gamma_c^2}{\lambda^2} B^2 A^2 - \frac{c\xi^2}{\lambda^2} (\Delta R) + 2\frac{c\gamma_a}{\lambda^2} \frac{\beta}{\lambda \mu} (\tilde{f} - f^*_S) \lambda^2 p_2$. Note that $\Delta R > 0$. By following same line of reasoning as above, we can show that there exists at least one root (say, $p_2$) that is $> 0$ $\Rightarrow qp^2 + rp + s \geq 0 \forall p \geq p_2$.

Note that the above proof is for the set of conditions ($\Theta_2$) such that $\xi^*_h < 1$. For the set of conditions ($\Theta_1$) such that $\xi^*_h = 1$, the proof proceeds similarly by replacing $\frac{\mu}{\mu}$ with $1$. Note that the only relevant case under $\Theta_1$ is $\tilde{f} > f^*_S$.

Finally, in the relationship $f^*_S = \tau \xi^*_h \xi^*_o$, we have (from Proposition 3) $\xi^*_o = \frac{f^*_S}{\xi^*_h} = \frac{c(1 - q_s) \lambda^2 \mu^2}{p_3 \lambda^2 \mu^2 \tau^2}$. Thus, $p_3 = \frac{c(1 - q_s) \lambda^2 \mu^2}{q_s \lambda^2 \mu^2 \tau^2} \Rightarrow \xi^*_o \leq 1$, or that the OPO is better-off.

The result follows by setting $p_o = \max\{p_1, p_2, p_3\}$.

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