Designing Efficient Resource Procurement and Allocation Mechanisms in Humanitarian Logistics

We analyze the efficacy of different resource procurement and allocation mechanisms in the design of humanitarian logistics-based supply chains. As a part of their preparedness effort, aid programs often make decisions on resource procurement and allocation ex-ante because doing so allows for rapid response if an adverse event occurs. However, such programs typically operate under funding constraints and donor earmarks, which makes the design of efficient resource procurement and allocation systems a challenging problem. We formulate this problem in an agency setting with two independent aid programs, where different resource procurement and allocation mechanisms are considered and where investments in resources are of two types: a primary resource that is needed for providing the aid, and infrastructural investments that improve the operation of the aid program in using the primary resource. We show that allowing aid programs the flexibility of transferring primary resources improves the efficiency of the system by yielding greater social welfare than when this flexibility does not exist. More importantly, we show that a central procurer can further improve system efficiency by providing a mechanism that facilitates the transfer of primary resources and eliminates losses from gaming. This outcome is achieved without depriving the individual aid programs of their decision-making autonomy while maintaining the constraints under which they operate. We find that outcomes with a centralized procurement system but decentralized infrastructural investments by the aid programs are the same as with a completely centralized system (where both procurement and infrastructural investments are centralized).

Key words: resource procurement; humanitarian logistics; supply chain design
History:

1. Introduction

The field of humanitarian logistics has recently been receiving greater attention as scholars recognize similarities and differences in the specific needs of supply chains in response to disasters vis-à-vis supply chains in the private sector (Van Wassenhove 2006, Gupta 2011). One important difference in the nature of these supply chains is the set of objectives targeted by profit versus non-profit organizations (Tomasini and Van Wassenhove 2009a). Yet there are many other differences between the design requirements of humanitarian logistics systems and those of corporate supply chains. Logistics involved in disaster response are typically reactive and are set up temporarily with specific functional elements in mind (Jahre et al. 2009), but they still require extensive planning and coordination for successful operation (Balcik et al. 2010). Such planning and coordination activities are often needed in advance of the actual events and must bear potential factors (e.g., geography, regional sensitivity to future events) in mind. Thus, the planning of humanitarian logistics systems has three main focus areas: preparedness, response, and collaboration (Tomasini and

Van Wassenhove 2009b).

To facilitate rapid response to adverse events such as natural disasters, it is imperative that humanitarian aid logistics programs establish their resource needs as early as possible and acquire their primary resources. An obvious example would be transportation assets like trucks, which have to be adapted to the various situations in which their deployment is an appropriate response. The aid programs are required to invest in an infrastructure to adapt these primary resources, e.g., logistics or maintenance skills, driver training. Resource planning and allocation are therefore important aspects of the preparedness and response activities of aid organizations. In this paper, we analyze the allocation and use of expensive resources by humanitarian logistics programs under the context-specific field conditions that make these activities a complex and challenging problem. First, in contrast to corporate supply chains (which are financed by revenues from ongoing operations) and to entrepreneurial ventures (which are financed from private and corporate venture capital), aid programs typically operate under conditions of insufficient financial resources. Second, if a donor has provided resources to an organization that is addressing some particular situation, then the donor likely and reasonably expects that the resources will be used for that situation. In this way the funding for resources is "earmarked", which makes it difficult for aid programs to share or pool resources. We analyze a set of transfer mechanisms and ownership structures for aid programs that operate under these constraints, and we investigate the efficacy of different mechanisms for achieving the benefits of collaboration.

We shall ask the following questions. Can mechanisms be designed to provide primary and secondary usage rights to different aid programs and thereby maximize the efficiency of humanitarian aid programs in the presence of resource constraints? What is the nature of such mechanisms? Can these mechanisms obtain the coordinated solution to the joint problem of multiple aid organizations? What is the role of central planning agents in such systems?

To study these questions, we use a general model to formulate the problem of two aid programs in three different settings: (1) when no transfer of primary resources is allowed between the aid programs; (2) when each aid program is allowed to procure its own primary resources and can also transfer them to another program (provided the other program needs the resource and the program that owns it does not); and (3) when a central procurer acquires the primary resource and loans it to one program, which can return the resource (for use by another program) if it does not need the primary resource. We also model each program as making upfront program-specific infrastructural investments to facilitate effective use of the primary resource. Building infrastructure to effectively use primary resources has a long lead time, and hence such investments must be sunk at the beginning of the planning period. We characterize the overall utility derived by the different parties in each of these three cases and then compare the net social welfare generated by the different cases. Our setup includes two critical, practice-driven features of the parties' humanitarian aid efforts. First, we model the primary resource as being expensive, so only one party can acquire the primary resource. Second, the funding provided by donors is earmarked, so that the resources cannot be jointly acquired and used by the two aid programs. Third, the programs maintain autonomy in making program-specific infrastructural investment decisions.

Our results may be summarized as follows. We first show that a rank ordering exists between the net social welfare generated by the three cases just described, and we show that the social welfare in Case 3, with the central procurer, is the highest. We also show that the net social welfare generated in this case is equal to the system-optimal social welfare, which means that it is possible for system efficiency to be maximized even under the constraints of expensive resources, donor earmarks for specific programs, and autonomy in decision making for the aid-programs. In this scenario, the central procurer either can extract all the additional surplus generated by the system or can subsidize the operating cost of the two aid programs; thus, we show that aid program designs involving a central procurer can achieve a wide variety of objectives. If each program is allowed both to invest and to transfer resources, as in Case 2, then the net social welfare generated is higher than with the system in which resource transfer is not allowed (i.e., Case 1).

Our results indicate that the design of systems for procuring large assets should be centralized under the aegis of a centralized body empowered to make appropriate allocation decisions to individual programs. We remark that the equivalence of outcomes for centralized procurement systems to a completely centralized system is achieved by maintaining the decision-making autonomy of individual aid programs, and respecting the donor earmarks and scarcity of funding constraints.

In short, we model operational conditions whose relevance is supported both by practice and by the literature on the design of resource planning and allocation systems for humanitarian aid programs. We show that system designs in which individual aid programs are responsible for procuring their primary resources are suboptimal and that their efficiency can be improved by centralizing the procurement process. If individual programs do procure their own primary resources directly, then giving each program the right to transfer the primary resource yields greater welfare benefits than denying that option. The mechanisms developed in this paper provide normative guidelines for the optimal design of procurement systems capable of resolving the practical constraints—mainly resource shortage, earmarks, and autonomy—faced by humanitarian aid organizations.

The rest of the paper is organized as follows. In the next section, we provide an overview of the literature on investments in preparedness and response and of past studies addressing collaborative efforts in humanitarian logistics. Section 3 details the model's assumptions and formulation as well as our analysis of the model results. We conclude in Section 4 by summarizing the paper's contributions and outlining directions for future research.

2. Extant Literature

The literature on designing resource procurement and allocation systems can be divided into the streams directed at the functions of preparedness, response, and collaboration (Kovacs and Spens 2007, Apte 2009, Tomasini and Van Wassenhove 2009b). In the area of resource preparedness, Ozdamar et al. (2004) study the planning of emergency logistics for adverse events (e.g., future natural disasters) as a vehicle routing problem, Barabarosoglu et al. (2002) analyze helicopter logistics for disaster relief operations, and de Silva (2001) studies planning methodologies for evacuation. Salmeron and Apte (2010) explore a two-stage stochastic optimization problem; the first stage focuses on designing the supply chain for relief resources, and the second stage focuses on response logistics. Similarly, Hwang (1999) studies the design of a food distribution system that could be deployed in the event of a natural disaster. Long (1997) examines the role of information systems in determining the success of disaster relief operations. Our paper differs from this stream of literature in that we focus on the coordination of multiple aid programs to solve a more generalized problem in the design of resource procurement and allocation systems.

In the literature on disaster response, Murray (2005) finds that humanitarian aid programs are employing many of the best logistical practices used in corporate supply chains to reduce lead times and improve response quality. Pettit and Beresford (2005) analyze the efficiency of using a mix of military and nongovernmental aid agencies to provide emergency relief response. Several studies consider the role of infrastructure and transport connectivity in the response to natural disasters (e.g., Long and Wood 1995, Cassidy 2003). Our paper differs from that stream of literature because it focuses on the procurement and investment of resources in the preparedness phase of responding to adverse events such as natural disasters.

Finally, a number of studies consider the collaboration between different aid programs in humanitarian logistics. There is ample empirical and anecdotal evidence of precious little collaboration or coordination between different aid agencies in response to adverse events (Chomilier et al. 2003, McClintock 2005, Murray 2005). A lack of collaboration can lead to the duplication of some efforts and to insufficient scale in others (Simpson 2005). Collaboration need not be limited to nongovernmental organizations; it can also include the private sector and local communities (Tomasini and

Van Wassenhove 2009a, Starr and Van Wassenhove 2011). There are many other references to humanitarian logistics in the literature, and this number is rapidly exploding. The key point to be made here is that nearly all of this work assumes a central decision maker, little or no resource constraints, and non-earmarked funds. However, the reality of humanitarian organizations is precisely that they are almost always highly resource constrained, decentralized and subject to earmarked funding. For instance, Pedraza Martinez et al. (2010) study the alignment of incentives to coordinate a fleet of vehicles owned by different aid programs. Our paper contributes to the collaborative stream of research by analyzing the impact of differently designed mechanisms (for resource procurement and allocation) on the potential of collaboration between aid programs constrained by scarce funding and donor earmarks.

3. Model Description, Formulation, and Analysis

In this section, we describe the model setting and state our assumptions. The sequence of events in our model is as follows. There are two aid programs, $i = A, B$, and each program needs a primary resource in the event that aid must be provided. A primary resource must be lined up ex ante, before the planning horizon, because the lead time necessary to acquire primary resources can be long. For simplicity think about vehicles and two distinct regions of a country. We assume that the probability of an adverse event requiring assistance from program i is given by p_i. In addition to procuring the primary resource, both programs must also make specific, up-front investments in building an "infrastructure" for effectively utilizing the primary resource. We use x_A and x_B to denote the respective program-specific infrastructural investments made by parties A and B. If an adverse event occurs for either party i, then providing aid services in response to that event yields the utility $u_i(x_i)$ for the affected party—provided the primary resource is at its disposal. We shall make the following four assumptions regarding the model parameters and problem constraints.

Assumption 1: Funding for resources is earmarked, so aid programs cannot share resources. This assumption reflects our observations in the field: donors require that funding provided for a specific purpose actually be used for that purpose.

Assumption 2: Aid program i's utility from responding to an event with the infrastructural investment x_i is given by $u_i(x_i)$; here $u_i(x_i)$ is strictly concave and increasing, $u_i(0) = 0$, and $u_i'(0) = \infty$. That response utility is strictly positive; however, this assumption does not mean that the program benefits from the event. Rather, the program accrues utility from having secured a primary resource that enables it to respond immediately to any event.

Assumption 3: The primary resource is so expensive that only one program has the funds to acquire it, and the other program does not. Without loss of generality, we assume a priori that

Program A has the capital needed to purchase the resource but that Program B does not. Mathematically, we assume that $\max_{x_B \geq 0} u_B(x_B)p_B - x_B < c$ and $\max_{x_B \geq 0} u_B(x_B)p_B - x_B > cp_B$, where c is the cost of the resource. Hence Program B would derive positive utility from the primary resource if an event occurred, even though an investment in the primary resource is not ex ante justified for this program. For Program A, we assume that $\max_{x_A \geq 0} u_A(x_A)p_A - x_A > c$. This assumption thus reflects the scarcity of funding faced by aid agencies and also captures the opportunity cost of such capital.

Assumption 4: The programs are not profit oriented. More specifically, we assume that if a program has the resource and if a disaster occurs that requires its response, then the program will utilize the resource and not transfer it to another program (even when it could earn a surplus from doing so). Since Program A has access to sufficient funding, in Case 2 we rule out the option of not procuring the primary resource upfront even if it could earn a surplus by a transfer from Program B. In Case 3, Program A has the priority of using the primary resource. In the completely centralized system, we assume that Program A has primary rights to the resource (in order to maintain system fairness). In other words, this assumption is based on our field observations, which establish that donors insist on resource utilization for a specific, earmarked purpose.

3.1. Model Formulation and Analysis

In this section, we discuss and analyze our three paradigmatic cases. We begin by describing the first case, in which the aid programs (A and B) make their decisions to acquire the primary resource independently and neither program is allowed to transfer that resource.

3.1.1. Primary Resource Nontransferable. Program B will not acquire the primary resource in this case because $\max_{x_B \geq 0} u_B(x_B)p_B - x_B < c$ (Assumption 3). Here $u_B(x_B)$ is B's utility if an event occurs and if it has made an infrastructural investment of x_B, and p_B is the probability that an adverse event occurs to which Program B must respond. The expected utility of B is therefore given by $u_B(x_B)p_B - x_B - c$ if it invests in the primary resource and makes an additional infrastructural investment of x_B. Assumption 3 is B's rationality constraint, whose violation in this case reflects the scarcity of funding faced by aid programs. Therefore, Program B will not acquire the primary resource.

By Assumption 3, Program A's net surplus is $u_A(x_A)p_A - x_A - c$, which is positive for some values of x_A; hence A finds it feasible to acquire the primary resource. Program A's problem is given by

$$\max_{x_A \geq 0} u_A(x_A)p_A - x_A - c.$$

It is easy to see that Program A should make the up-front infrastructural investment given by $u_A^{'}(x_A^*) = 1/p_A$, where x_A^* is the solution to A's problem. We compute the net social welfare in this case, which is equal to the combined utility surplus of the two programs. Because neither acquiring the primary resource nor investing in specific infrastructure is optimal for Program B, the joint utility in this case is $\Pi_1 = u_A(x_A^*)p_A - x_A^* - c$; here Π_1 denotes the net social welfare in Case 1. Next we derive the net social welfare when both programs are allowed to make infrastructural investments in the primary resource but only one party actually acquires it, with the option to transfer that ownership if it does not need the resource.

3.1.2. Primary Resource Transferable If Not Utilized by Acquirer. In this case, either both programs acquire the primary resource or only one does (we assume, without loss of generality, that it is Program A) even though both programs make infrastructural investments for it (Habib and Johnsen 1999). The program that owns the primary resource has the first right of use, but the resource can be transferred if this program does not actually need to utilize it. In order to determine the transfer price of the primary resource, we use the Nash bargaining rule.

Note that, in this case also, Program B does not independently acquire the primary resource because doing so would violate B's individual rationality constraint. Yet B can still make infrastructural investments related to the primary resource acquired by A, which it will do by Assumption 2 ($u_B^{'}(0) = \infty$). We start by determining the transfer price at which Program A will transfer the primary resource to Program B if A does not need the resource. The expected Nash bargaining surplus is given by $[u_B(x_B) - p_T]p_B(1-p_A)p_T$, where p_T is the transfer price and the bargaining takes place with probability $p_B(1-p_A)$; under this bargaining rule, the surplus accruing to Program B is given by $u_B(x_B) - p_T$ and the surplus for Program A is given by p_T. Note that the A's surplus does not include its investments in the primary resource and infrastructure, since they are sunk. The result is a transfer price of $p_T = \frac{1}{2}u_B(x_B)$. We next characterize the infrastructure-specific investments of both aid programs.

Program A's problem is

$$\max_{x_A \geq 0} u_A(x_A)p_A + \frac{1}{2}u_B(x_B)p_B(1-p_A) - x_A - c.$$

It is clear that x_A^* solves Program A's problem, where x_A^* is as in Section 3.1.1. Program B's problem is

$$\max_{x_B \geq 0} \frac{1}{2}u_B(x_B)p_B(1-p_A) - x_B.$$

It is also easy to see that Program B should make the infrastructural investment given by $u_B^{'}(x_B^*) = 2/p_B(1-p_A)$, where x_B^* is the solution to Program B's problem.The joint utility in this case is $\Pi_2 = u_A(x_A^*)p_A + u_B(x_B^*)p_B(1-p_A) - x_B^* - x_A^* - c$, where Π_2 denotes the net social welfare in Case 2. We now compare the net social welfare in Case 2 with that in Case 1.

Proposition 1: *The net social welfare when the primary resource is transferable is greater than when it is not transferable; that is,* $\Pi_2 > \Pi_1$.

Proposition 1 is of interest because it confirms that the flexibility of transferring primary resource ensures greater welfare for both programs—even though the assets cannot be jointly owned and one of the programs cannot afford to acquire the primary resource. Observe that investing in the primary resource does not directly add utility to either program; rather, the flexibility of having the primary resource to justify up-front infrastructural investments yields a higher utility for Program B, which can now provide services should an adverse event occur within its territory. However, Program A also benefits from that flexibility because it can count as a surplus the funds that it earns from the transfer when it does not utilize the resource.

Finally, we analyze the case of a central procurer owning the primary resource and leasing it to one of the two programs with the option to reclaim the primary resource if it is not utilized.

3.1.3. Primary Resource Acquired by Central Procurer. In this case a central procurer acquires the primary resource and offers the first right of using it to Program A. As before, both programs make respective up-front infrastructural investments of x_A and x_B. If Program A exercises its right to use the primary resource, then it must pay the central procurer the cost c and also an interest payment I_A. If A does not utilize the resource, then it makes no payments to the central procurer. Including a fixed cost to Program A for this option does not change the model's results. In that case, the central procurer may then sell the resource to Program B for $c + I_B$, assuming B needs the resource. Program A's problem of determining its optimal infrastructural investment may be written as

$$\max_{x_A \geq 0} u_A(x_A)p_A - x_A - (c + I_A)p_A.$$

It follows easily that x_A^* is the solution to Program A's problem. Program B's problem is

$$\max_{x_B \geq 0} u_B(x_B)p_B(1-p_A) - x_B - (c + I_B)p_B(1-p_A).$$

Let $\tilde{x}_B$ be the solution to B's problem; that solution is characterized by $u_B^{'}(\tilde{x}_B) = 1/p_B(1-p_A)$. The joint utility in this case is $\Pi_3 = u_A(x_A^*)p_A + u_B(\tilde{x}_B)p_B(1-p_A) - \tilde{x}_B - x_A^* - c$, which is the net social welfare of the entire system in Case 3 (i.e., the combined utilities of A and B and of the central procurer, too). We now compare the net social welfare generated in this case with that in Case 2.

Proposition 2: *The net social welfare when the primary resource is transferable between two programs (Case 2) is less than when a central procurer acquires the primary resource and then issues primary and secondary rights to the respective programs (Case 3); that is,* $\Pi_3 > \Pi_2$. *Program A makes the same infrastructural investment in Cases 2 and 3, whereas Program B makes a greater infrastructural investment in Case 3 than in Case 2.*

Proposition 2 shows that the central procurer can Pareto-increase the two programs' infrastructural investments to levels that exceed those obtained in Case 2. The central procurer has two advantages compared to Case 2 where the two programs mutually agree on a resource transfer mechanism without the involvement of a third-party.

First, the central procurer eliminates the loss of efficiency due to the gaming in the system that occurs in Case 2 because of the bargaining process that determines the transfer mechanism between the programs. Second, the central procurer mitigates the need for the programs to acquire the primary resource up front, which helps both programs, as now they only need to make their infrastructural investments up front. In Case 2, Program A had to acquire the primary resource up front, and ran the risk that this investment may not have been recouped if the adverse event did not happen. So that the central procurer is not transferring the financial burden of the primary resource, it can structure the interest payments I_A such that A is left with the same expected utility as in Case 2. Note that I_A may be such that Program A's expected utility is higher than in Case 2. Program B could be offered a subsidy (i.e., negative I_B) — which is a payment from the central procurer to B if it is required to facilitate B's use of the primary resource.

It is most interesting that the central procurer increases overall efficiency by extracting efficiency gains from within the system, and these gains can be used (if needed) to subsidize a program's use of the primary resource. Therefore, this design of a humanitarian logistics system Pareto-dominates the flexibility mechanism of Case 2.

Corollary 1: *The interest payments* I_A *and* I_B *can be set in such a way that* $v_i^1 < v_i^2 \leq v_i^3$ *for* $i \in \{A, B\}$*, where* v_i^j *denotes the expected utility of program* i *under Case* j*.*

We now investigate whether the results of the system with a central procurer can be improved.

Proposition 3: *The net social welfare with a system that includes a central procurer (Case 3) is equal to that with a completely centralized system that employs the same resource allocation policy and also entails centralized decision making for the infrastructural investments. With the* *central procurer decentralized decision making in infrastructural investments does not induce any inefficiency.*

Proposition 3 shows that the net social welfare obtained by Case 3 cannot be improved upon, and this bears several interesting implications for the design of humanitarian logistics supply chains. Moreover, centralized procurement features a number of advantages (e.g., standardization of equipment and quantity discounts from suppliers), as noted in the literature (Tomasini and Van Wassenhove 2009a). We have shown that such systems have the additional advantage of enabling aid programs to make greater infrastructural investments by relieving those programs of the need to acquire expensive primary resources ex ante.

As mentioned previously, this paper takes into account three constraints from our field studies: the existence of earmarked budgets, decentralized decision making, and funding constraints. In this section we have shown that the efficiency of humanitarian logistics systems can be improved—while continuing to operate within the restrictions and principles of donors and other authorities—by a central procurer empowered to make resource acquisition decisions. Note that even with the central procurer, individual programs make their own infrastructural investment decisions as well as decisions to acquire the resource from the central procurer. It is interesting to note that several large International Humanitarian Organizations (IHO) have recently moved toward such a system, most notably, the International Federation of Red Cross and Red Crescent Societies.

4. Conclusions, Discussion, and Future Research

Our paper considers the design of a supply chain for humanitarian logistical operations—in terms of resource preparedness, response, and collaboration—from the perspective of two independent aid programs that may need to act in response to future adverse events. We consider the problem with two different investments: an aid program invests in a primary resource, one that is necessary for providing aid but in itself provides no other utility, and makes an additional, infrastructural investment whose utility is increasing in the amount invested. We also model three constraints that are widely observed in the field of humanitarian logistics, but unfortunately often ignored in academic research: aid programs are often strapped for the funds needed to acquire expensive resources ex ante, donors frequently provide funding that is earmarked for a specific purpose and, programs maintain autonomy in decision making. In this context, we consider the problem of resource acquisition and infrastructural investments that must be made under different supply chain designs and then compare the net social welfare obtained in each of these systems.

We first consider a system in which the two programs operate independently of each other and without the flexibility to transfer resources—even when one program has no use for an acquired primary resource. This is our benchmark system because field observations indicate that it accurately represents the actual operations of many humanitarian logistics systems. We then contrast the net social welfare obtained if instead the two programs were allowed to transfer resources among themselves should the need arise. We show that flexibility in primary resource transfers increases the system's net social welfare. Finally, with respect to designing the logistics of a system for delivering humanitarian aid, we demonstrate that the central procurer fulfills two roles: it eliminates gaming between the aid programs; and it provides an efficient interface for transferring assets from one program to another.

As mentioned above, some IHO have recently moved or are seriously considering moving to such a system. Needless to say, these change projects often encounter considerable cultural and political hurdles since they tend to go against deeply ingrained habits in very decentralized organizations with multiple donors, poor management information systems, and are frequently characterized by a lack of transparency and trust. However, these implementation issues are the subject of further research. It is also interesting to note that several initiatives are underway to create inter-organizational platforms for centralized procurement of expensive assets as suggested by our results. Given the even larger challenges when trying to create these structures across organizations, time will tell if they will indeed appear soon. Our guess would be that a higher frequency of disasters, reduced funding, and increased pressure for more effective use of donor money will indeed accelerate these developments.

The contribution of this paper is twofold. First, the development of our model is based on observations of humanitarian logistics systems in practice—that is, while considering the constraints under which these systems operate. Given that aid programs must make up-front investments in different types of resources that may or may not be used, improving the design of such systems under these constraints should increase the efficiency of usage of donor funding. Second, we show that systems with central procurers offer efficiency gains over systems that rely on transfer mechanisms between programs. Central procurement plays an important role in all three dimensions (i.e., preparedness, response, and collaboration) because it enables humanitarian logistics operations to incorporate them more easily into their resource procurement and allocation functions. This is in stark contrast to supply chains in the private sector, for whom profit is the primary objective. Although some corporate supply chains benefit from coordination imposed by a third party, the central procurer described in Case 3 of this paper is more efficient in that it can use its accrued surplus to subsidize programs in need, thereby increasing net social welfare.

In short, our results yield normative recommendations for improving the design of resource procurement and allocation in humanitarian supply chains. These findings strongly suggest that partners in the design of such systems could make better decisions than heretofore concerning the structures used for resource procurement and allocation, and the framework proposed in this paper can serve as a prescriptive model in that regard.

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Appendix

Proof of Proposition 1: It is easy to see that $u_A(x_A)p_A - x_A - c$ is concave, as $u_A(x_A)$ is strictly concave by assumption. Hence, the first-order condition for the infrastructural investment x_A gives the optimal value of x_A^*, where $u'_A(x_A^*) = 1/p_A$. Therefore, $\Pi_1 = u_A(x_A^*)p_A - x_A^* - c$. If the primary resource is transferable (Case 2), Program A's optimal investment is x_A^*, which is the same as Case 1. Program B's optimal infrastructural investment (x_B^*) is given by: $u_B^{'}(x_B^*) = \frac{2}{p_B(1-p_A)}$.

The joint utility in this case is $\Pi_2 = u_A(x_A^*)p_A - x_A^* - c + u_B(x_B^*)p_B(1-p_A) - x_B^* > u(x_A^*)p_A - x_A^* - c = \Pi_1$.

Proof of Proposition 2: In Case 3, Program A's optimal investment is x_A^*, which is the same as Case 1 and 2. Program B's optimal investment $\tilde{x}_B$ is characterized by $u_B^{'}(\tilde{x}_B) = \frac{1}{p_B(1-p_A)}$. Since

$u_B(\cdot)$ is an increasing concave function, it is easy to see that $\tilde{x}_B > x_B^*$. The joint utility in this case is $\Pi_3 = u_A(x_A^*)p_A + u_B(\tilde{x}_B)p_B(1-p_A) - \tilde{x}_B - x_A^* - c$. Note that by definition of $\tilde{x}_B$,

$$\Pi_3 > u_A(x_A^*)p_A + u_B(x_B^*)p_B(1-p_A) - x_B^* - x_A^* - c = \Pi_2 > \Pi_1.$$

Hence, Case 3 leads to the highest social welfare for the system.

Proof of Corollary 1: Note that $v_A^1 = u_A(x_A^*)p_A - x_A^* - c$, $v_A^2 = u_A(x_A^*)p_A - x_A^* - c + \frac{1}{2}u_B(x_B^*)p_B(1-p_A) > v_A^1$. From Case 3, $v_A^3 = u_A(x_A^*)p_A - x_A^* - (c + I_A)p_A$. Note that the interest term I_A does not affect the program's investment decision. Set I_A such that $u_A(x_A^*)p_A + \frac{1}{2}u_B(x_B^*)p_B(1-p_A) - x_A^* - c = u_A(x_A^*)p_A - x_A^* - (c+I_A)p_A$. Therefore, we have $v_A^2 = v_A^3$.

Similarly, $v_B^2 = \frac{1}{2}u_B(x_B^*)p_B(1-p_A) - x_B^* > 0 = v_B^1$. For Case 3, $v_B^3 = u(\tilde{x}_B)p_B(1-p_A) - \tilde{x}_B - (c + I_B)p_B(1-p_A)$. Set I_B such that $\frac{1}{2}u_B(x_B^*)p_B(1-p_A) - x_B^* = u_B(\tilde{x}_B)p_B(1-p_A) - \tilde{x}_B - (c+I_B)p_B(1-p_A)$. Therefore, we have $v_B^2 = v_B^3$.

Therefore Case 3 Pareto-dominates Cases 1 and 2. From the central procurer's perspective, in the first two cases there is no cost. In Case 3 the cost to the central procurer is

$$c - (c+I_A)p_A - (c+I_B)p_B(1-p_A) = (u_B(x_B^*)p_B(1-p_A) - x_B^*) - (u_B(\tilde{x}_B)p_B(1-p_A) - \tilde{x}_B) < 0.$$

Note that the central procurer may use this surplus to subsidize the programs by setting $I_A$and $I_B$in such a way that $v_i^2 < v_i^3$, as its surplus is strictly positive.

Proof of Proposition 3: In such a centralized system, the total surplus is $u_A(x_A)p_A + u_B(x_B)p_B(1-p_A) - x_B - x_A - c$. Therefore the centralized system's investment problem is

$$\Pi_c = \max_{x_A, x_B \geq 0} u_A(x_A)p_A + u_B(x_B)p_B(1-p_A) - x_B - x_A - c\ .$$

It is easy to verify that that $x_A^*$and $\tilde{x}_B$solve the above maximization problem. Therefore, $\Pi_3 = \Pi_c$.