Journal of International Technology and Information Management

Volume 27 | Issue 3 Article 2

1-1-2019

A Game-Theoretic Approach to Share the Costs of Cooperating Healthcare Networks

Jay M. Lightfoot
University of Northern Colorado, jay.lightfoot@unco.edu

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University of Northern Colorado

ABSTRACT

The growing demand for healthcare services combined with the disarray in the health insurance market in the United States has created a situation where rival health networks are aggressively competing by building duplicate health facilities and providing redundant services in localized geographic regions. Unfortunately, this strategy can reduce the quality of patient care and decrease profits (Kaissi & Charland, 2013). A solution to this problem is for health networks to cooperate and share healthcare equipment, facilities, and personnel. Toward that end, this paper presents a game-theoretic method that can share these costs in a fair, efficient, and repeatable manner.

KEYWORDS: Cooperative game-theory, Shapley simplification, joint venture, healthcare networks

INTRODUCTION

The healthcare industry in the United States is in disarray. The combination of an aging population, instability in the insurance market due to the uncertainty of the Affordable Care Act (ACA), soaring healthcare costs due, in part, to excessive litigation, and inefficient "fee-for-service" billing practices have created a very difficult situation for all healthcare stakeholders. Insurance companies struggle to determine how much to charge for coverage while physicians feel hamstrung in their ability to provide proper care within the limitations of insurance coverage. Hospital administrators attempt to balance the needs of patients, care-givers, and stockholders while still adhering to government rules and regulations. Finally, patients are forced to navigate a byzantine system where they are often required to purchase a service without having any idea how much it will cost or who will pay for it. Clearly, this is far from an optimal situation.

A conspicuous consequence of this chaotic environment is the proliferation of healthcare provider facilities by competing health networks, often within relatively small geographic areas (Levine & Linder, 2016). The primary intent of this strategy is to capture insured (i.e., paying) customers through convenience and proximity to services (Chang, et al., 2015; Fine & Frazier, 2011). This is especially true for emergency trauma facilities, since rules exist that require transport to the closest trauma center with the appropriate trauma-level rating. On the surface, this tactic appears beneficial to consumers because competition normally lowers prices while easier access to services should be advantageous to healthcare customers. However, an unintended consequence of this trend is that it can lead to a situation where costs for health services increase, provider profits decrease, and community access to healthcare services potentially can be eroded (Kaissi, et al., 2013; Weiss, 2004). This is due, in part, to the unnecessary duplication of expensive healthcare equipment, facilities, and personnel. By working independently and eschewing cooperation, rival healthcare networks are missing a potential synergy that would benefit all.

A better, more economically rational approach would be for competing health networks to share the cost of expensive medical equipment, facilities, and personnel through cooperative joint ventures so that all can utilize these resources in an efficient manner. While not a universal solution to all the problems mentioned above, it could mitigate the costly consequence of healthcare resource duplication. Doing so would not violate the intent of existing antitrust legislation (Leibenluft, 2015). In addition, profitable operations could still continue through specialized services and dedicated facilities while the customer base as a whole would benefit through decreased costs.

Unfortunately, this ideal solution has been difficult to achieve because it requires a method that is perceived as both fair and neutral to divide the cost of those healthcare resources among the competing participants. This allocation algorithm would also need to be understandable and repeatable to incentivize participants to maintain a stable coalition. With this in mind, the primary motivation for this research project is to introduce a cost sharing method with these characteristics and to determine its viability in a realistic competitive healthcare scenario. This will not only help competing healthcare services in the United States, but is also applicable to healthcare systems that are more closely managed by the government in other countries.

THE HOSPITAL ADMINISTRATOR'S PERSPECTIVE

The factors responsible for the proliferation of healthcare facilities and services are extremely complex and cannot be understood merely by performing a review of the literature. Consequently, the initial step taken in this project was to contact and interview the Chief Executive Officers (CEO) of three regional healthcare networks. The CEOs each had over 30 years of healthcare administrative experience and oversee, in total, thirteen acute and critical care hospitals in the Colorado and Wyoming region. The intent of the interviews was to gather their perspectives on the current healthcare environment and to gauge their reaction to the notion of sharing the cost of healthcare resources. Overall, the CEO's responses, which are summarized below, were surprisingly consistent and were quite useful in focusing this research on areas where it has the best chance for successful implementation.

Extreme Competition

The CEOs confirmed that the level of competition in the healthcare market is very high. One used the word "predatory" to describe the interaction between competing networks while another used the word "ferocious." When asked about healthcare construction, one mentioned that the current flurry of construction of new facilities was not based on anticipated demand, but rather was intended to lure customers from the other networks. While it is true that demand for healthcare services is growing, the CEOs related that consumer demand is not growing fast enough to justify the current level of new construction projects.

Healthcare Culture

Each CEO stated that the healthcare culture does not naturally encourage sharing and cooperation. One said that he could not think of a single case where two competing health networks had decided to collaborate on a joint purchasing venture. This indicates that there is a strong streak of independence in the healthcare profession. This is particularly true with physicians, who generally like to think of themselves as autonomous agents. This tendency is tempered by the reality that they require access to expensive hospital resources to practice medicine; however, there is still a residual culture that resists sharing unless necessary. Evidence of this can be found in the adherence to the inefficient and confusing "fee-for-service" billing practice favored by the industry. Despite this, the CEOs were united in their optimism that the culture was changing and that cooperative ventures were inevitable given the expense of new technology and the impact of the Affordable Care Act.

Dynamic Environment

It goes without saying that the healthcare environment is dynamic. New medical procedures are continually being developed and the legal landscape of healthcare insurance in the United States is rapidly changing. Because of this, the CEOs interviewed were hesitant to give specific predictions about the level or type of resource sharing that is likely to occur. However, all were confident that joint ventures would Increase and that healthcare would improve for consumers in the future.

"Medical Arms Race"

A common theme voiced during the interviews was that healthcare networks are engaged in a "medical arms race" that requires competing networks to acquire the latest medical equipment in an effort to demonstrate their cutting-edge status. As one CEO put it, "First we had to have MRI machines, then we had to have PET scanners, now everybody expects us to have Di Vinci [robot surgery] devices." Modern medical equipment is extremely expensive and, according to the interviews, not always efficiently utilized; however, from a marketing standpoint it is required to present the image of a healthcare network on the "bleeding-edge" of technology. The downside of this race is that the utilization of these devices is generally too low to recoup fully the initial cost before the next new technology is introduced. This was viewed by one of the CEOs as a factor that will encourage resource sharing in the future.

Healthcare Marketing

Competing health networks are very concerned about the perceived marketing image of their brand. The image they want to project is one of professional competence, caring, convenience, and high technology. Along these lines, the convenience factor is a prime motivator for new construction projects. The rationale is that placing healthcare facilities near the customer has a better chance of capturing market share. One CEO related a story about how the location for a new hospital facility was chosen specifically because it was mid-way between two hospitals of a competing chain, effectively diminishing the convenience of the competition. Based upon the interviews, it is obvious that this type of thinking is a prime reason why collaborative ventures have been rare in the past.

Other Constraints to Cooperation

In addition to the factors mentioned above, the CEOs identified additional barriers to cooperation. First are the rules used to accredit trauma centers into the various trauma levels within the system. Achievement of a particular trauma center level depends on the on-site availability of specific resources and personnel. Centers with the higher trauma levels provide more elaborate services. If a center depends on remote, shared resources it would likely be certified at a lower trauma level which would reduce its status in the region. Given that trauma patients are usually admitted into the hospital associated with the center, this could reduce patient counts and profits. A second constraint to collaborative ventures relates to the population density of the geographic area. Some medical services that could easily be shared in a high-density metropolitan area cannot in rural areas where the distance between care units is unreasonably large. Essentially, the level of care would decrease if patients were expected to travel long distances to utilized shared services and resources. Finally, there is concern about anti-trust legislation and how existing anti-trust laws will be applied in the new era of the Affordable Care Act. While the ACA encourages cooperation and consolidation, there is a good deal of ambiguity concerning how the courts will interpret its application. The CEOs are wary of running afoul of government regulators and facing an anti-trust lawsuit. The primary take-away from these concerns was that cooperative sharing is desirable but cannot be all-encompassing across all healthcare resources. Thus, the constraints listed above impose boundaries on the viable sharing options.

Likely Sharing Opportunities

The information gathered through the interviews indicated that cooperative joint ventures for all medical resources is unlikely; however, the CEOs did have several suggestions on areas where sharing across competing networks is possible and desirable. Specifically, the shared clinic facility building could be shared if centrally located along with medical imaging equipment (e.g., MRI, PET scan, Di Vinci devices) as long as it was scheduled appropriately. This would not be feasible for trauma centers due to the certification rules, but could work in other, non-emergency settings, especially in densely populated metropolitan areas. In addition, specialized personnel such as radiologists and surgeons were prime candidates for sharing since they can be scheduled and their skills shared across multiple locations. Finally, ancillary services such as ambulance, pharmacy, laundry, data processing, insurance, and bill collections were identified as likely candidates for cost sharing. Based on this knowledge, these are the areas on which this research focused.

PRIOR RESEARCH

A large body of research exists concerning the various ways to share the cost of cooperative joint ventures. A key concern throughout this literature is that these costs be shared in a "fair" manner that creates a *stable* coalition. That is, a sharing solution where there is no incentive to break away from the coalition and proceed independently. Solutions with this characteristic are formerly said to be in the *core*. Sharing solutions without a core are possible, but there would be economic pressure for one or more of the participants to leave the coalition, so they tend to be less stable (Buchholz, Haupt, & Peters, 2014). Other desirable characteristics include a solution that is *efficient* (i.e., fully allocates the cost or savings), *repeatable* (i.e., not negotiated), and *understandable*. Of these characteristics, the one that is most ambiguous is that the allocation be "fair." This is due to the fact that fairness is in the eye of the beholder and is often a severe obstacle to cooperation (Cruijssen, Cools, & Dullaert, 2007). Common perspectives on fairness include the following (Kolker, 2014; Thomson, 2016):

- Equal division – Share the cost equally among all participants. This is sometimes called *egalitarian* division.
- Proportional division – Allocate the cost in proportion to some other factor such as gross sales or proportional use of the resource.
- Negotiated division – Share the cost based on cooperation and compromise.
- Pareto Optimal division – Divide the cost or savings in a balanced way so that no one can benefit without harming other participants in the joint venture.

Egalitarian methods tend to be unstable because the solution would seldom be in the core and some participants could fare better by proceeding independently. Likewise, proportional division tends to generate solutions that vary significantly from stability (Özener, Ergun, & Savelsbergh, 2013; Verdonck, Beullens, Caris, Ramaekers, & Janssens, 2016). Negotiated division can produce stable results that are efficient, but the negotiation process is time-consuming and costly and the results may not be repeatable due to the dynamic nature of the process (Bond & Gasser, 1988). Hence, for the purposes of this research, the Pareto Optimal approach to fairness will be pursued because it is the most likely to produce stable, predictable, and repeatable solutions. It is also the approach that best aligns with the competitive healthcare environment described by the hospital CEOs.

Surprisingly, given the large number of possible cost sharing methods, the literature in this area has focused on relatively few approaches with the desirable theoretical and empirical characteristics mentioned above (Anshelevich et al., 2008). Of these, the Nucleolus and the Shapley value are the two most promising (Kolker, 2014;

Owen, 1995). Both the Nucleolus and the Shapley value can produce stable, efficient, unique (i.e., single point) solutions that would be in the core for joint ventures in the healthcare environment (Fiestras-Janeiro, Garcia-Jurado, & Mosquera, 2011; Guajardo & Rönnqvist, 2016; Schmeidler, 1969). These solutions would also be Pareto Optimal and repeatable. However, a key concern with the Nucleolus approach is that it is not a formula-based calculation. It instead relies on complex iterative linear programming techniques that can be difficult to setup and apply (Guajardo & Rönnqvist, 2016; Kolker, 2018). In addition, it can produce solutions where some participants pay less if the total cost increases or pay more if the total cost decreases, thus setting up undesirable incentives (Kolker, 2018). This limits its usefulness in real-world situations. Consequently, the Shapley value was the method chosen for this research project because it exhibits all the desirable solution characteristics and is considered fair (in the Pareto Optimal sense), equitable, stable, and neutral by virtually all researchers (Boatsman, Hansen, & Kimbrell, 1981; Frechette, et al., 2016).

SHAPLEY VALUE COST SHARING

The Shapley value is a game-theoretic approach that provides a potential solution to the cost allocation problem addressed by this research. The Shapley value was developed by Lloyd Shapley in 1953 as an algorithmic way for *players* in an *abstract game* to determine the outcome of that game prior to actually playing it (Shapley, 1953). Since its development, the Shapley value has been used in a wide variety of real-world contexts. It has, for example, been used in the areas of electricity transmission allocation, freight transportation, natural resource sharing, determining uncertainty factors in simulation models, and evaluating deposit insurance premiums (Fiestras-Janeiro, et al., 2011; Guajardo & Rönnqvist, 2016; Song, Nelson, & Staum, 2016; Staum, 2012). In the healthcare context, it has been used to identify gene sub-groups prominent in ovarian cancer research, optimize supply chain networks for hospitals, and help reduce false alarms in intensive care units (Afghah, Razi, & Najarian, 2015; Mohebbi, 2015; Razi, Afghah, & Varadan, 2015).

The result generated by the Shapley value is a unique, single-point solution that allocates to each participant the average of the marginal cost that participant creates by joining the collaborative venture (Guajardo & Rönnqvist, 2016). Said another way, the Shapley value generates a solution that is at the "center of gravity of the extreme points of core" when the core exists (Shapley, 1971). The formula to calculate the Shapley value is given below (Shapley, 1953).

$$x_i = \sum_s \left[\frac{(s-1)!\,(n-s)!}{n!}\right] * [c(S) - c(S - [i])] \quad (1)$$

Where:

c = coalitions of players
n = number of players in the "grand coalition"
n! = number of coalition permutations
i = an individual player
s = number of coalitions containing i
x_i = cost allocated to player i
c(S) = coalition containing S
[c(S) - c(S-[i])] = contribution that an individual player makes to a coalition

The Shapley formula is relatively easy to apply, so it has the benefit of being understandable and repeatable. Its use, however, has been somewhat limited because the information requirements needed to calculate the value grow exponentially as the number of *players* (i.e., participants) in the joint venture increases. For example, the Shapley value requires the development of $2^n - 1$ cost sharing scenarios where '*n*' is the number of participants in the joint venture. So, a 4-player game (i.e., joint venture) requires 15 cost scenarios, a 5-player game requires 31, and so on. For any collaborative venture with more than a few participants, the information requirements quickly become overwhelming. A solution to this limitation is to utilize simplifications to the Shapley value that have been developed for special classes of problems. These simplifications generate identical allocations for any number of players without the corresponding computation and information burden. Consequently, because of the favorable characteristics of the Shapley value and the existence of Shapley simplifications that can overcome the primary limitation to using it in practical contexts, the remainder of this research focuses on using Shapley simplifications to share the cost of healthcare collaborative ventures.

SHAPLEY SIMPLIFICATIONS

The healthcare environment described by the CEOs identified categories of resources that could be shared by three Shapley simplifications. As mentioned previously, these simplifications generate the same results as the full Shapley value, but do not have unreasonable input data requirements. Specifically, the data input requirements grow linearly with the number of players rather than exponentially. This characteristic allows the value to be calculated for much larger, realistic-sized, joint ventures. The sections below introduce the simplifications and the Appendix of this paper demonstrates their potential use in sharing the cost of healthcare resources.

PARALLEL SYSTEM SIMPLIFICATION

Littlechild and Owen (1973) developed a simplification for classes of shared resources with overlapping requirements where the cost to any subset of players is equal to the cost to the largest player.

If a game v_s has the structure

$$\boldsymbol{v_s} = \begin{bmatrix} a \\ b \\ c \\ b \\ c \\ c \\ c \end{bmatrix}$$

where $a \leq b \leq c,$ then its Shapley value is:

$$\begin{aligned} x_1 &= \tfrac{1}{3}\, a \\ x_2 &= \tfrac{1}{3}\, a + \tfrac{1}{2}(b-a) \\ x_3 &= \tfrac{1}{3}\, a + \tfrac{1}{2}(b-a) + (c-b) \end{aligned} \qquad (2)$$

SERIAL SYSTEM SIMPLIFICATION

The cost of another class of resources can be shared by determining the total quantity of the resource required and multiplying it by the cost for each "unit." This is appropriate for resources that are independently purchased and used solely by each player in the game. Using this simplification produces the same sharing solution as using the full Shapley value (Lightfoot, 1990).

If a game v_s has the structure

$$\boldsymbol{v_s} = \begin{bmatrix} a \\ b \\ c \\ a+b \\ a+c \\ b+c \\ a+b+c \end{bmatrix}$$

then its Shapley value is:

$$\begin{aligned} x_1 &= a \\ x_2 &= b \\ x_3 &= c \end{aligned} \qquad (3)$$

STEPWISE SERIAL SIMPLIFICATION

Some resources must be purchased in pre-determined, indivisible quantities or capacities. For example, if a coalition of healthcare providers wants to share the cost of several ultrasound devices, these machines must be acquired in whole "units," that is, no partial ultrasound devices can be purchased. So, if 3.3 ultrasound machines were needed by the joint venture, the coalition would buy 4 to satisfy the demand. This type of "lumpy" resource can be shared using the stepwise serial simplification as shown below (Lightfoot, 1990).

If a game v_s has the structure

$$v_s = \begin{bmatrix} v(1) \\ v(2) \\ v(3) \\ v(12) \\ v(13) \\ v(23) \\ v(123) \end{bmatrix} = \begin{bmatrix} m1 \\ m2 \\ m3 \\ m12 \\ m13 \\ m23 \\ m123 \end{bmatrix} \begin{array}{l} = \text{Cost of min } \{M_k\text{:}M_k \geq a\} \\ = \text{Cost of min } \{M_k\text{:}M_k \geq b\} \\ = \text{Cost of min } \{M_k\text{:}M_k \geq c\} \\ = \text{Cost of min } \{M_k\text{:}M_k \geq a+b\} \\ = \text{Cost of min } \{M_k\text{:}M_k \geq a+c\} \\ = \text{Cost of min } \{M_k\text{:}M_k \geq b+c\} \\ = \text{Cost of min } \{M_k\text{:}M_k \geq a+b+c\} \end{array}$$

where M_1, M_2, … are the available resource sizes, then its Shapley value is:

$$\begin{aligned} x_1 &= m_1 + \tfrac{1}{2}(m_{12}-m_1-m_2) \\ &\quad + \tfrac{1}{2}(m_{13}-m_1-m_3) \\ &\quad + \tfrac{1}{3}(m_{123}-(m_{12}+m_{13}+m_{23}-m_1-m_2-m_3)) \\ x_2 &= m_2 + \tfrac{1}{2}(m_{12}-m_1-m_2) \\ &\quad + \tfrac{1}{2}(m_{23}-m_2-m_3) \\ &\quad + \tfrac{1}{3}(m_{123}-(m_{12}+m_{13}+m_{23}-m_1-m_2-m_3)) \\ x_3 &= m_3 + \tfrac{1}{2}(m_{13}-m_1-m_3) \\ &\quad + \tfrac{1}{2}(m_{23}-m_2-m_3) \\ &\quad + \tfrac{1}{3}(m_{123}-(m_{12}+m_{13}+m_{23}-m_1-m_2-m_3)) \end{aligned} \qquad (4)$$

All three simplifications, when applied to the proper class of resource, will result in a sharing solution identical to what would be produced using the full Shapley value. In addition, all three are generalizable to sharing coalitions with any number of players. This removes the primary limitation to using Shapley allocations in practical contexts. The following section will demonstrate its use in a healthcare example.

APPLICATION OF THE APPROACH

For this illustration, assume that three competing hospitals form a joint venture to share the cost of a centralized imaging clinic with DNA sequencing capabilities in a large metropolitan area. The initial arrangement is to share the cost of the clinic facility, a CT scanner, DNA sequencers, a team of radiologists, computers, and laundry service. Later, depending upon the success of the collaboration, the cost of other resources could be shared. The characteristics of the shared resources are described below.

- The three hospitals have overlapping requirements for the clinic facility with hospital A needing a 9,000 ft^2 facility and hospitals B and C requiring 15,000 ft^2 and 19,000 ft^2 respectively. The building is estimated to have a final cost of $400 per square foot to complete. Given that a large percentage of the clinic is devoted to waiting rooms and administrative offices, the group agreed that the 19,000 ft^2 building will satisfy all three.
- Radiologist cost an average of $400,000 per year in the metropolitan area. Hospital A anticipates a workload requiring .8 of a full-time radiologist while hospital B would need 2.1 and C would require 2.7. Since radiologists can only be “purchased” in whole units, the clinic will hire a team of 6 radiologists to handle the workload.
- Laundry service, while a minor clinic expense, is representative of several ancillary services that could eventually be shared. Laundry service can be purchased for 60 cents a pound with a 10% quantity discount on loads exceeding 500 pounds. Hospital A anticipates generating 50 pounds of laundry a week and B and C will produce 150 and 175 pounds per week respectively. This shared total will not qualify for the quantity discount, so the cost sharing allocation will use the serial simplification initially. Later, if the volume exceeds 500 pounds, the stepwise simplification can be used to allocate the cost.
- The clinic requires a shared CT scanner, several DNA sequencers, and computers for the staff. The resource details and associated costs of these resources are provided in the Appendix of this paper. The Appendix also demonstrates how to apply the simplifications to calculate a cost sharing

solution. The results of all the cost allocations in the joint venture are shown in Table 1. This table also shows what the cost to each hospital and the collective would have been without the joint venture.

Table 1: Cost Allocation for 3-Hospital Example

Resource	Purchase Scenario	Hospital A $	Hospital B $	Hospital C $	Total Cost $	Simplification
CT Scanner	No Joint Venture	400,000	1,000,000	2,500,000	3,900,000	
	Shapley Allocation	133,333.33	433,333.33	1,933,333.33	2,500,000	Parallel
DNA Sequencers	No Joint Venture	2,550,000	1,700,000	850,000	5,100,000	
	Shapley Allocation	1,983,333.33	1,558,333.33	708,333.33	4,250,000	Stepwise
Laundry Service	No Joint Venture	300	390	570	1,260	
	Shapley Allocation	300	390	570	1,260	Serial
Computers	No Joint Venture	25,000	44,000	63,000	132,000	
	Shapley Allocation	18,933.33	33,533.33	54,733.33	107,200	Stepwise
Radiologist	No Joint Venture	400,000	1,200,000	1,200,000	2,800,000	
	Shapley Allocation	333,333.33	933,333.33	1,133,333.33	2,400,000	Stepwise
Clinic Facility	No Joint Venture	3,600,000	6,000,000	7,600,000	17,200,000	
	Shapley Allocation	1,200,000	2,400,000	4,000,000	7,600,000	Parallel
Total Allocation $	No Joint Venture	6,975,300	9,944,390	12,213,570	29,133,260	
	Shapley Allocation	3,669,233	5,358,923	7,830,303	16,858,460	

  ISSN: 1941-6679-On-line Copy

DISCUSSION

The key to using the Shapley value to allocate resource costs for cooperating healthcare providers is to classify the individual resources based upon their characteristics and then apply the appropriate simplification to each. These individual costs can then be added together to determine the total cost allocated to each participant. This not only makes the problem computationally easier, but also aligns with the sharing environment described by the hospital administrators. If the resources are not treated separately, a Shapley solution can still be calculated, but it would require creating 2^n - 1 coalition cost scenarios and using the original Shapley formula. While not a major problem in the proof-of-concept clinic example, a larger coalition of hospitals would require an unreasonable number of scenarios. Thus, the simplifications allow Shapley value allocations to be applied in a real-world context.

The three-hospital solution shown in Table 1 shares the cost of six resources. The table provides the outcome of using the Shapley simplifications and of proceeding independently for each resource. Based on the results shown in Table 1, each hospital, and the collective as a whole, will save a significant amount of money by cooperating. Three of these resources are shared using the stepwise simplification, two are shared with the parallel simplification, and one uses the serial simplification. The decision concerning which simplification to use depends on the characteristics of the resource. For example, the stepwise simplification was used for the DNA sequencer, computer, and radiologist resources because each of these must be purchased in whole units. You cannot buy a fractional DNA sequencer; consequently, the general rule for this category is that the cost of any medical resource that must be purchased in indivisible units (with or without quantity discount) can be shared using the stepwise simplification. The CT scanner and the clinic facility were shared using the parallel simplification because a larger resource (i.e., a bigger building and more advanced CT scanner) would satisfy the needs of the hospitals with more modest requirements. For this category, the general rule is to use the parallel simplification when a larger capacity resource can satisfy users with smaller requirements. Finally, the serial simplification was used for the shared laundry service. This resource is representative of a category of ancillary services that would need to be shared to create a workable joint venture. It would not be reasonable to expect each hospital to independently contract with a separate laundry service for the clinic. Even if sharing the cost of laundry services did not save any money, the logistics and complexity of not sharing would be burdensome. (However, with sufficient volume, quantity discounts would likely be offered which would result in a cost savings.) The same would be true for similar clinic functions such as bill collection and pharmacy services. So, the serial simplification is applicable for those healthcare situations where the service/resource is required, the units of service used are variable and divisible, and it would be impractical not to cooperate in the purchase.

FUTURE RESEARCH

The research presented in this paper was intended to show proof-of-concept and the viability of the cost sharing technique in a realistic hospital scenario. The resource requirements used in the case scenario were derived directly from information provided by the hospital CEOs. Likewise, the prices used in the case were based on the current actual cost of the equipment and resources listed in the scenario. The cost sharing method is applicable to coalitions of any size due to the characteristics of the Shapley Value and its simplifications; consequently, it is not limited to the "3-player game" used in the example case. Given this, the first phase of the research project was successful.

Subsequent work on this project will involve communicating the results of the research to the hospital CEOs originally interviewed. The intent is to gauge their acceptance of the approach and to collect more information about possible applications. This information will be used to refine the technique and possibly account for other real-world factors such as the impact when hospitals of significantly different sizes cooperate and how the method could be used when healthcare networks merge. These are realistic considerations that will make the technique more robust. The outcome of this phase of the research project will hopefully lead to its application in an actual healthcare cost sharing venture.

CONCLUSION

The healthcare industry is currently underutilizing its capital and human resources by pursuing unnecessary, and economically unwise, competition. The result of this strategy has been shown to decrease provider profits and negatively impact the quality of patient care (Kaissi & Charland, 2013). It is possible and desirable for competing health networks to cooperate in targeted joint ventures to mitigate this problem. Toward that end, this paper has demonstrated an approach using simplifications of the Shapley value that will make it easier to setup stable collaborative joint ventures between competing healthcare networks.

The application of this approach was illustrated using a realistic example where three hospitals cooperated to share the cost of an imaging clinic. The results of applying the Shapley simplifications to the example confirm that the sharing solution produced is stable because each hospital saves money by cooperating and no hospital (or sub-group of hospitals) can do better by breaking away from the joint venture. In addition, the solution is fair, in the Pareto Optimal sense, because no hospital can be allocated a smaller cost without another hospital having to pay more. It divides the total cost of the resources (no more, no less) and is formula-based, so it is efficient and repeatable. Finally, the solution produced for the clinic is understandable in that it does not require knowledge of game theory or advanced mathematics to apply.

The Shapley simplifications themselves do not have unreasonable input data requirements; therefore, they overcome the primary limitation to applying the Shapley value to non-trivial problems. For the Serial and Parallel simplifications, one data value is needed for each player in the coalition; so, a 10-player coalition would only need 10 input data values. The Stepwise simplification does require $2^n - 1$ inputs; however, only one value for each player must be provided. The remaining inputs can be generated by merely adding together and rounding up the requirements of the individual players to the next whole unit. Thus, the approach is computationally feasible for large joint ventures where economies of scale are greater.

There are limits to the type of resources that could, in practice, be shared in a collaboration among competing healthcare networks. As previously noted, emergency room trauma centers are not good candidates for resource sharing due to certification requirements. Also, services where real-time turn-around is required would not easily be shared. For example, tissue pathology diagnosis is often required during surgery to determine if more aggressive procedures are required. The lab performing the diagnosis of the samples needs to be close to the surgery center, so a remote shared pathology lab would not work. Also, sharing any critical medical resource in remote rural areas is problematic due to the travel time involved in reaching the shared site. Despite these situations where sharing in not feasible, a broad range of other collaborative opportunities are available. By utilizing the approach introduced in this paper, it will be possible for competing healthcare networks to take advantage of the economic synergies available through collaboration and cooperation.

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APPENDIX

The calculations below apply the Shapley simplifications to several of the resources listed in the 3-hospital case. Note: a "3-player" joint venture scenario was used to demonstrate the viability of the cost sharing method. While the simplifications produce results identical to using the full Shapley value with coalitions of any size, this case was limited to three hospitals to reduce the complexity of the example.

CT SCANNER

Parallel Simplification: The three hospital networks will purchase and share use of a new Aquilion One Vision CT scanner. Hospital X_1 has modest general-imaging requirements and wants a 16-slice scanner ($400,000) to meet their needs. Hospital X_2 has higher volume requirements and also wishes to offer vascular imaging services which need better quality images, so they require a 128-slice system ($1,000,000). Finally, hospital X_3 wishes to setup a cutting-edge imaging facility capable of high volume cardio studies; consequently, they require a 640-slice scanner ($2,500,000). Given the expected usage volume, all three hospitals could share a single 640-slice machine with this cost allocation.

Resource Cost	Player Requirement	Cost to "go it alone"
16-slice: $ 400,000	S(1): 16-slice $400,000	X_1 = 400,000
128-slice: $ 1,000,000	S(2): 128-slice $1,000,000	X_2 = 1,000,000
640-slice: $ 2,500,000	S(3): 640-slice $2,500,000	X_3 = 2,500,000
		==========
		$ 3,900,000

Shapley Sharing Solution

X_1 = ⅓ (400,000) = 133,333.33
X_2 = ⅓(400,000) + ½(1,000,000 – 400,000) = 433,333.33
X_3 = ⅓(400,000) + ½(1,000,000 – 400,000) + (2,5000,000 – 1,000,000) = 1,933,333.34
============
$ 2,500,000.00

AUTOMATED DNA SEQUENCING

Stepwise Simplification: The three hospitals also wish to acquire automated DNA sequencing equipment that will allow them to do in-house DNA analysis. After reviewing available products, it is decided that the Illumina NovaSeq 5000 system, at an installed cost of $850,000, offers the best combination of features and capacity. Based on anticipated volume, hospital X_1 requires 2.1 sequencers, hospital X_2 requires 1.4 sequencers, and hospital X_3 requires .7 sequencers. Given that only whole units can be purchased (that is, you cannot purchase fractional sequencers), the joint venture will require the purchase of 5 machines. The allocation to divide the $4,250,000 is:

Resource Cost		Player Requirements			Cost to "go it alone"
1 sequencer:	$850,000	S(1):	2.1	$ 2,550,000	X_1 = 2,550,000
2 sequencers:	$1,700,000	S(2):	1.4	$ 1,700,000	X_2 = 1,700,000
3 sequencers:	$2,550,000	S(3):	.7	$ 850,000	X_3 = 850,000
4 sequencers:	$3,400,000	S(12):	4.0	$ 3,400,000	=========
5 sequencers:	$4,250,000	S(13):	3.0	$ 2,550,000	$ 5,100,000
		S(23):	3.0	$ 2,550,000	
		S(123):	5.0	$ 4,250,000	

Shapley Sharing Solution

X_1 = 2,550,000 + ½(3,400,000-2,550,000-1,700,000) +
½(2,550,000-2,550,000-850,000) +
⅓(4,250,000-(3,400,000+2,550,000+2,550,000 -
2,550,000-1,700,000-850,000)) = $ 1,983,333.33

X_2 = 1,700,000 + ½(3,400,000-2,550,000-1,700,000) +
½(2,550,000-1,700,000-850,000) +
⅓(4,250,000-(3,400,000+2,550,000+2,550,000 –
2,550,000-1,700,000-850,000)) = $ 1,558,333.33

X3 = 850,000+ ½(2,550,000-2,550,000-850,000) +
½(2,550,000-1,700,000-850,000) +
⅓(4,250,000-(3,400,000+2,550,000+2,550,000 –
2,550,000-1,700,000-850,000)) = $ 708,333.34

============
$ 4,250,000.00

COMPUTERS

Serial Simplification: The hospitals in the collaborative venture plan to purchase computers to be used by in the clinic. Their requirements are as follows: hospital X_1 needs 10, hospital X_2 needs 22, and hospital X_3 needs 35. The notebook computers cost $2,500 each and would not be shared between users. Without quantity discounts, the cost division is as follows.

Cost Each	Player Requirements	Shapley Sharing Solution
\$2,500	S(1): 10	X_1 = 10 * 2,500 = 25,000
	S(2): 22	X_2 = 22 * 2,500 = 55,000
	S(3): 35	X_3 = 35 * 2,500 = 87,500
		=======
		\$ 167,500

Stepwise Simplification: Quantity discounts are common when purchasing large numbers of computers, so assume that a volume purchasing agreement for computers was negotiated with the following price schedule.

Quantity	Cost each
1 to 10	\$2,500
11 to 25	\$2,000
26 to 50	\$1,800
> 51	\$1,600

Using the stepwise simplification, the cost sharing solution for the joint purchase would be:

Player Requirements		Cost to "go it alone"
S(1):	10 * 2500 = \$ 25,000	X_1 = 25,000
S(2):	22 * 2000 = \$ 44,000	X_2 = 44,000
S(3):	35 * 1800 = \$ 63,000	X_3 = 63,000
S(12):	32 * 1800 = \$ 57,600	=======
S(13):	45 * 1800 = \$ 81,000	\$ 132,000
S(23):	57 * 1600 = \$ 91,200	
S(123):	67 * 1600 = \$107,200	

Shapley Sharing Solution

X_1 = 25,000 + ½(57,600-25,000-44,000) + ½(81,000-25,000-63,000) + ⅓(107,200-(57,600+81,000+91,200-25,000-44,000-63,000)) = \$ 18,933.33

X_2 = 44,000 + ½(57,600-25,000-44,000) + ½(91,200-44,000-63,000) + ⅓(107,200-(57,600+81,000+91,200-25,000-44,000-63,000)) = \$ 33,533.33

X_3 = 63,000+ ½(81,000-25,000-63,000) + ½(91,200-44,000-63,000) + = \$ 54,733.33

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\$ 107,200.00

ISSN: 1941-6679-On-line Copy