PARTIAL REMUNERATION FOR CAPACITY TO STABILIZE SUBCONTRACTOR RESOURCE ALLOCATIONS

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ABSTRACT

A novel formula for payment to subcontractors, which shifts some of the risk for reduced productivity due to plan instability from the subcontractor to the general contractor, is proposed. The formula requires that a price for capacity be set as well as a price for product, with a single weighting parameter to balance between them. Using a three player game theory based simulation, use of the formula has been shown to lead to resource allocation behaviours that benefit all parties in unstable or average conditions, but has no effect under stable conditions.

KEY WORDS

economic game theory, production system design, remuneration for capacity, resource allocation, subcontracting

INTRODUCTION

Earlier research (Harel and Sacks 2006; Sacks and Harel 2006a) showed that subcontracting can have a destabilizing effect on construction projects where subcontractors carry the risk of low productivity of their staff resulting from schedule instability. When the scheduled work assignments are not stable, trade teams run the risk of standing idle while waiting for completion of precedent activities, information, materials, equipment, or other prerequisites for their tasks (Koskela 1992). Waiting time reduces overall productivity. Where their subcontractor employer is remunerated according to unit prices or a lump sum – which is the case in the majority of construction subcontracts – a fall in productivity reduces profitability and can lead to financial losses. The less stable the project, the more susceptible trade subcontractors are to losses of this kind.

Some standard contracts, such as the AGC Subcontract for Building Construction, give the general contractor the right to dictate the time and pace of works with no consideration of any capacity constraints of the subcontractor (Tommelein and Ballard 1997), and have no explicit compensation mechanism. Other standard contracts, such as the JCT 05 Standard Building Subcontract (Barnes 2006) and the FIDIC 'Red Book' (Seppala and Ragazzi 1994), do consider the possibility of compensation for losses due to reduced productivity. However,

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there is no explicit remuneration for such losses; rather, the subcontractor can only claim losses subsequent to performance of the work. The entire onus of proof and record-keeping is on the subcontractor, and it must succeed in proving that productivity was reduced as a direct result of some action or omission on the part of the general contractor (REF p.238). In many cases, such as when a preceding subcontractor slows work and delays the subcontractor in question, it is difficult to prove the liability of the general contractor.

Thus, in the absence of effective contractual safeguards, the two most common ways in which subcontractors counteract this risk are to allocate fewer resources to projects where they perceive the project manager's plans to be unrealistic, or to allow buffers of time and work in progress (WIP) to accumulate ahead of their crews (Sakamoto et al. 2002; Tommelein et al. 1999).

Project managers are acutely aware of this strategy, and tend to respond by exaggerating their demands for resources in the first place, in the hope that the reduced supply will match their actual real needs (Harel and Sacks 2006). A vicious circle results, in which projects and subcontractors function in a stable lose-lose equilibrium. Research using game theory models has confirmed survey findings which showed that subcontractors' resource allocation behaviour is dictated primarily by their perceptions of workflow stability. The impact of sanctions or fines on their behaviour is weak, particularly where labor is the major cost component of their services (Sacks and Harel 2006a).

Yet subcontracting offers general contractors many advantages over direct employment of labour (Edwards 2003; Hsieh 1998; Maturana et al. 2007). Efficiencies that rely on trade specialization are one; flexibility in the face of unstable demand and construction projects that have wide varieties of buildings systems is another. The extent of subcontracting in modern construction has been documented in numerous studies; a 1998-99 study of general contractors in commercial construction in the US found that 91% of the trades were subcontracted more than 75% of the time (Costantino and Pietroforte 2002).

Thus a pertinent question for research is "How can general contractors enjoy the benefits of subcontracting without suffering extended project durations that result from unreliable provision of labor?" The Last Planner System helps in this regard by making projects more stable, which in turn reduces the risk for subcontractors to suffer productivity losses (Ballard 2000; Sacks and Harel 2006b). However, it does not change the basic rules of engagement that are the root cause of unreliable resource allocation behavior to begin with.

Changes to the basic mode of subcontracting, as expressed in the contract itself, appear necessary. Using the economic and game theory models developed earlier, an alternative formula for remuneration, in which the general contractor assumes some of the risk for labour productivity, has been investigated.

ECONOMIC MODEL AND RESEARCH METHOD

Most subcontractors perform work on multiple projects simultaneously. For work under unit price or lump sum contracts, the income to be earned, or the loss incurred, by a subcontractor in any particular project over a single planning period can be expressed as a function of the prices and costs for each work item performed, the quantity of work planned for, the production resources actually applied, and the quantity of work actually made available. Equation (1), which expresses the net income, is a succinct expression of a model developed by Sacks (Sacks 2004):

$$I_n \approx \min[k,q]W_D(U - C_M) - kW_D C_S \quad ..(1)$$

The variables are defined in Table 11. The net income depends on the amount of work actually performed and the cost of the resources incurred. The first term on the right hand side, $\min[k,q]W_D(U - C_M)$, represents the total income from the work actually performed; it is the smaller of either the work actually made available (represented by the factor q) or the capacity of resources actually provided (factor k). The second term, $kW_D C_S$, represents the total cost of the resources actually provided by the contractor.

Table 1. Annotation.

Parameter	Definition
I_n	Net income from project *I* during any period *T*.
W_D	Quantity of work planned by the general contractor in period *T*.
W_A	Quantity of work that is actually made available in period *T*.
q	The ratio of the quantity of work actually made available to that planned during any period *T*. $q = W_A / W_D$. This is similar, but not identical, to the PPC measure of the Last Planner™ system. Unlike PPC, q may be greater than 1, because it measures the total amount of work made available, including any that may not have been planned. PPC is only concerned with the work made available that was in fact planned initially.
U	The unit price for the work set in the contract.
C_M	The cost of materials for each unit of the work.
W_D	Quantity of work planned by the general contractor in period *T*.
k	The ratio of the actual resources provided by the subcontractor to the quantity of resources needed to complete the full quantity of work planned in period *T*.
C_S	The cost of the resources per unit of work planned in period *T*. The total cost of resources to perform W_D is given by $W_D C_S$.

At the start of any given planning period, a subcontractor must decide on the quantity of resources to assign to each project at hand. The subcontractor knows the unit price, the unit costs of materials and resources and the amount of work planned (or demanded) by the general contractor's project manager. However, the actual value of q that will occur is not known with certainty. This is because work planned will only actually become available for execution through the planning period when all of the preconditions are fulfilled. The quantity of work actually made available also has a second order impact on income, because productivity itself is a function of work quantity and space (O'Brien 2000). However, here, the focus is on the subcontractors' strategy in allocating resources; for sake of simplicity, the second order effect, material waste and overheads are ignored.

The two starting points – multiple concurrent projects and the maximization of net income – can be jointly expressed by summing expression (1) over multiple projects:

$$I_n \approx \sum_{i=1}^{n} \left\{ \min[k_i, q_i] W_{D_i} \left(U_i - C_{M_i} \right) - k_i W_{D_i} C_{S_i} \right\} - C_R \quad ..(2)$$

Expression (2) adds the cost of any resources not allocated to any project. As unallocated resources are only a source of cost and cannot generate income, a subcontractor will attempt to avoid this situation. Given that there is uncertainty about the values of q_i at any time, there are two possible strategies:

- Contract for sufficient projects to ensure that the total amount of work likely to be made available will be greater than the total capacity of resources, in which case all resources can be gainfully employed. This strategy is termed overbooking.
- Where the total amount of work planned is less than the total capacity available, identify which projects are most reliable and/or where the amount of work planned may be underestimated, and set k>1. Thus situations may arise in any particular project where more resources are allocated than are needed according to the general contractor's work plan.

The parameters affecting the subcontractors' behavior can be compared using expression (1). Figure 11 shows the relationship between the quantity of resources allocated to any project (represented by k) and the income, I_n, and its dependence on the reliability of the project schedule (represented by q). As q declines, not only is the total income reduced, but the point at which losses are incurred occurs for increasingly smaller resource levels. Given this relationship, in order to maximize its income in any single project, a rational subcontractor must try to estimate the most likely value for q and allocate resources appropriately, (i.e. try to set $k = q$).

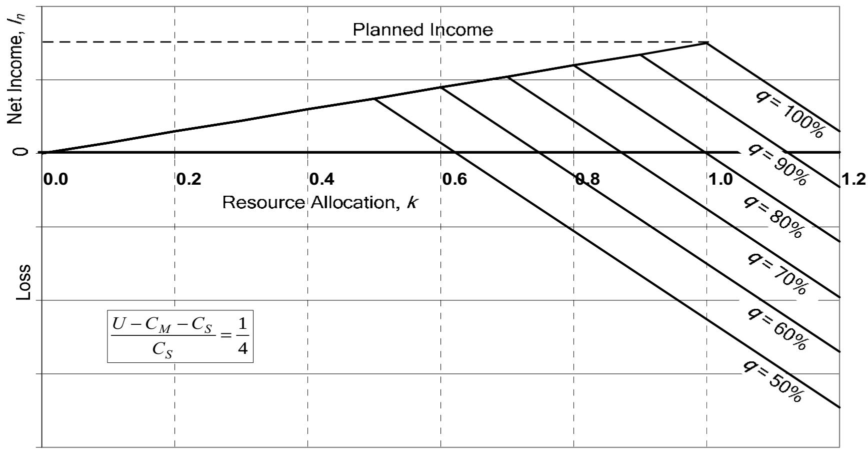

Figure 1. Relationship between net income, resource allocation and plan reliability (Sacks 2008) (reproduced with permission of Taylor and Francis Group).

GAME THEORY APPROACH

The game theory formulation developed by Sacks and Harel (2006a) modelled the allocation of resources at the start of each planning period in a project (typically each week). The players are a work planner (a project management function in traditional construction systems, denoted 'PM') and a subcontractor (SUB). In each round of the game, the PM sets the amount of work to be performed by the SUB in each task *i* in a planning period on the basis of the construction master plan. The SUB evaluates the demand and the amount of work they perceive will actually become available, and then supplies the resources they deem appropriate.

The parameter q (work actually available to the work initially planned) was represented by a probability distribution, P[q], which is essentially a measure of plan reliability at the site. The PM's possible moves are detailed using a ratio d, which is the ratio of the work demanded, W_D, to the work the PM estimates will become available, W_P. The value d is modelled by discrete values: demand resources for less work than estimated (d=0.9), exactly the amount estimated (d=1) and more than estimated (d=1.1). The SUB can then elect to allocate fewer resources than required for the work demanded (k=0.9), exactly the amount required (k=1) or more than demanded (k=1.1). The extensive form game was used. Each player could evaluate the utility for all players, but could not predict the value for q.

For each permutation of the values for q, d and k, the economic utilities for each player are calculated, resulting in expected outcomes for a 3x3 strategy two-player game for which the Nash equilibriums can be determined. The results for this two-player formulation are that when neither the PM nor the SUB has any knowledge of the probability distribution of q (i.e. neither can predict how much work will be possible) there is a perfect equilibrium, which is the strategy pair: PM demands more; SUB provides fewer.

The utilities represent sub-optimal performance for both SUB and PM.

When both have full knowledge of the work to be made possible there are two significant equilibriums. The first occurs when the PM demands more work in every case, and the SUB provides fewer resources in very case. The second occurs when exact resources are both demanded and allocated in every case (with optimal utilities - a win-win situation). However, both are idealized situations (both have some understanding of the project stability, but neither can have full knowledge of the future). Thus the game theory model showed that under normal unit price contract terms in projects with uncertainty (i.e. all projects) the natural economic behaviour will result in sub-optimal performance.

MULTI-PROJECT SUBCONTRACTED LABOUR ALLOCATION SIMULATION MODEL

However, the two player formulation is limited because it does not model the real-world dilemma subcontractors face when allocating insufficient resources among competing projects. To do this, a three player game was devised, in which a second project and its manager was introduced. Another key deficiency was addressed in the new model by expanding the utility function of the SUB to consider cash flow, risk of exposure and fines in addition to profit. The SUB utility is calculated using the formula

$$U_{SUB} = \sum_{q_A i, i=1}^{i=3} \sum_{q_B j, j=1}^{j=3} P_{Ai} * P_{Bj} (\alpha_1 * Income + \alpha_2 * CF - \alpha_3 * Fines),$$

in which income, cash flow (CF) and fines are dependent on the actual work provided, the strategies employed by each player, and the management style of each project manager (hard, medium or soft). The weighting factors α_1, α_2 and α_3 are set according to subcontractor type; six basic types, differentiated by their attitude to risk and their liquidity, were identified through interviews with field personnel.

Table 2 shows a typical result, in this case with a perfect equilibrium solution in which both project managers A and B exaggerate their demands for labour (*dA*=1.2, *dB*=1.2) and the subcontractor divides its resources without favouring either one or the other project (in this formulation, *k* = resources actually supplied to project A / resources available for project A). The model simulation, implemented using Gambit and Microsoft Excel software, serves as a test bed for exploring the interactions between the different motivating factors and conditions that affect subcontractors' resource allocation behaviour.

Table 2. Three player game utility matrix for Type 1 Subcontractor with PM A and PM B both ‘soft’. The equilibrium solution (dA=1.2, dB=1.2, k=1) is shaded.

PM A (Soft)	*SUB (Type 1)*	PM B (Soft) *dB*=1.0 U_{PM1}	*dB*=1.0 U_{SUB}	*dB*=1.0 U_{PM2}	*dB*=1.1 U_{PM1}	*dB*=1.1 U_{SUB}	*dB*=1.1 U_{PM2}	*dB*=1.2 U_{PM1}	*dB*=1.2 U_{SUB}	*dB*=1.2 U_{PM2}
	k=0.8	8.00	*4.57*	9.80	7.62	*3.80*	9.80	7.27	*3.09*	9.80
dA=1.0	*k=1.0*	9.40	*7.27*	9.40	9.07	*6.52*	9.50	8.76	*5.81*	9.58
	k=1.2	9.80	*6.55*	8.00	9.69	*6.54*	8.40	9.58	*6.52*	8.76
	k=0.8	8.27	*4.87*	9.72	8.00	*4.36*	9.80	7.65	*3.65*	9.80
dA=1.1	*k=1.0*	9.50	*6.99*	9.07	9.40	*6.84*	9.40	9.10	*6.13*	9.49
	k=1.2	9.80	*6.02*	7.43	9.80	*6.34*	8.00	9.70	*6.31*	8.37
	k=0.8	8.51	*5.13*	9.65	8.24	*4.61*	9.73	8.00	*4.15*	9.80
dA=1.2	*k=1.0*	9.58	*6.71*	8.76	9.49	*6.56*	9.10	9.40	*6.41*	9.40
	k=1.2	9.80	*5.53*	6.91	9.80	*5.85*	7.48	9.80	*6.13*	8.00

A HYBRID REMUNERATION FORMULA

Standard contractual arrangements between subcontractors (Barnes 2006) and general contractors make it very difficult to implement practical steps intended to improve flow according to lean construction principles. Most contracts have extensive provisions for dealing with non-conformance or non-performance on the part of the subcontractor, but very few provisions

– if any – for creating a stable workflow. The subcontract basis

inhibits the use of multi-skilled work cells and there are usually no provisions for shifting workload and/or labour and equipment between teams as conditions demand at any given time. The resulting behaviours make it difficult to improve stability and reduce variability in terms of the number of workers, the arrival times of crews on site, the availability of core equipment, etc.

However, even while critiquing the problems subcontracting poses for lean construction management, the benefits it provides – in terms of employment flexibility, competitiveness and trade specialization – cannot be ignored. Its primary flaw for the purposes of this discussion is the complete transfer of risk for reduced productivity from general contractor to subcontractor. In order to support considerations of work flow, and to facilitate application of lean construction techniques, this risk should be apportioned in accordance with the ability to control the risk. Some contracts create a safety net for subcontractors by allowing them to make claims for situations in which work does not become available as planned. This should not be left to subcontractors' claims for compensation, but built in *a priori* as an inherent part of each price, by splitting unit prices into two components – one to be paid for product, and the other for resource capacity. The payment for work would no longer be simply $I=WU$ (work completed multiplied by unit price), but:

$$I = W(1-\alpha)U + \alpha U_L D_A n \text{ , where } n = \min(n_D, n_A) \quad ..(3)$$

The term α is a measure of how much risk is shifted, and must be agreed to by both parties in advance. The second part of the right-hand side of equation 3 is composed of a unit labor cost per unit time, UL, the actual duration for the work, DA, and the lesser of the actual number of workers provided, nA, and the number of workers demanded, nD. The number of workers demanded should be capped for each task by the construction manager at a value which reflects his/her confidence about the rate at which work will be made available. Where they are less certain, managers will now demand less labour to avoid paying for excess. On the other hand, the subcontractor has good reason to meet the demanded resource level, in order to maximize its' income. The arrangement reduces a subcontractor's motivation to act defensively, because the potential losses due to under-employed resources are reduced. Figure 2 shows how a value of 50% for α shifts the intercept with the profit/loss dividing line to the right for different scenarios of plan stability (values of q).

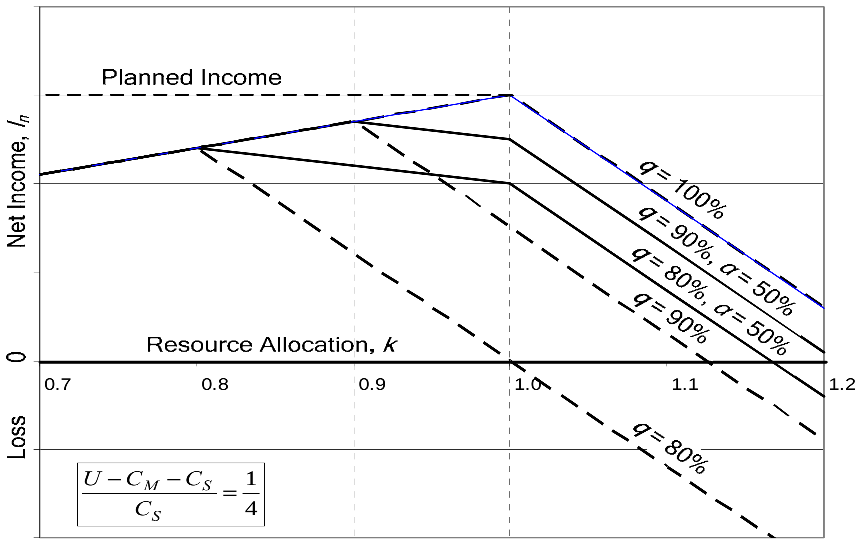

Figure 2. Adjusted relationship between net income, resource allocation and plan reliability (Sacks 2008) (reproduced with permission of Taylor and Francis Group).

ASSESSMENT OF THE HYBRID FORMULA

In the three player game theory model, with the proposed remuneration formula, the net income for the subcontractor using the hybrid formula is:

$$I_n \approx \min[k,q]W_D((1-\alpha)U - C_M) + \alpha U_L D_A \min[k,1]n_D - kW_D C_S \quad (4)$$

The expected effect of this remuneration formula under various conditions was explored using the three player simulation test bed. The results presented below illustrate project environments with three degrees of stability. The first, termed 'unstable' is characterized by low planning reliability in projects A and B and was modelled by applying a probability distribution for q (the amount of work actually provided) for both projects as follows:

P[q=0.8]=0.55, P[1.0]=0, P[1.2]=0.45. The second is 'average' stability, with a distribution: P[0.8]=0.3, P[1.0]=0.5; P[1.2]=0.2. The third is a 'stable' environment in which P[q=1.0]=1. Of the six subcontractor types that the model can simulate, type 1 was used – this subcontractor is risk averse and has critical liquidity levels. Three project manager types are considered – the 'hard' project manager (who is conservative when approving accounts and always imposes sanctions when labour is not supplied according to demand), the 'medium' PM and the 'soft' PM.

Table shows the set of equilibrium solutions for nine combinations of PM types and four levels of values for α for the first project manager (A); only PM A is using the hybrid payment formula for the subcontractor, while PM B maintains a traditional contract (α=0% for all cases). As can be seen, when α approaches 40%, more occurrences of stable demand (dA=1) begin to appear.

Table 3. Simulation results for unstable work environments in both projects.

Unstable α	0%		0%	20%		0%	40%		0%	50%		0%
PM A – PM B	dA	k	dB	dA	k	dB	dA	k	dB	dA	k	dB
Soft-Soft	1.2	1*	1.2	1.2	1.2	1.2	1	1.2	1.2	1	1	1.2
Medium-Soft	1.2	1.2	1.2	1.2	1.2	1.2	1	1.2	1.2	1	1.2	1.2
Hard-Soft	1.2	1.2	1.2	1.2	1.2	1.2	1	1.2	1.2	1	1.2	1.2
Soft-Medium	1.2	0.8	1.2	1.2	0.8	1.2	1.2	0.8	1.2	1	1	1.2
Medium-Medium	1.2	1*	1.2	1.2	1.2	1.2	1.1	1.2	1.2	1	1	1.2
Hard-Medium	1.2	1.2	1.2	1.2	1.2	1.2	1	1.2	1.2	1	1	1.2
Soft-Hard	1.2	0.8	1.2	1.2	0.8	1.2	1.2	0.8	1.2	1.2	0.8	1.2
Medium-Hard	1.2	0.8	1.2	1.2	0.8	1.2	1.2	0.8	1.2	1.2	1	1.2
Hard-Hard	1.2	1*	1.2	1.2	1.2	1.2	1.1	1.2	1.2	1.1	1	1.2
Expected Utilities	8.8	3.7	9.0	8.9	4.3	8.6	8.3	4.0	9.6	8.5	4.1	9.1
Joint Expected Utility for PM A & SUB	8.10			8.75			8.15			8.35		

* These values are averages of numerous strategies, not single values representing stable behaviour.

Table 4. Simulation results for average work environments in both projects.

Average α	0%		0%	20%		0%	40%		0%	50%		0%
PM A – PM B	dA	k	dB	dA	k	dB	dA	k	dB	dA	k	dB
Soft-Soft	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2
Medium-Soft	1.2	1	1.2	1.1	1.2	1.2	1	1.2	1.2	1	1.2	1.2
Hard-Soft	1.2	1.2	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2	1.2
Soft-Medium	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2
Medium-Medium	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2
Hard-Medium	1.2	1	1.2	1.2	1	1.2	1.1	1	1.2	1.1	1	1.2
Soft-Hard	1.2	0.8	1.2	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2
Medium-Hard	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2
Hard-Hard	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2	1.2	1	1.2
Expected Utilities	9.3	4.9	9.3	9.3	5.4	9.2	9.2	5.3	9.3	9.2	5.3	9.3
Joint Expected Utility for PM A & SUB	9.55			10.05			9.90			9.90		

Table 5. Simulation results for stable work environments in both projects.

Stable α PM A – PM B	0% dA	k	0% dB	20% dA	k	0% dB	40% dA	k	0% dB	50% dA	k	0% dB
Soft-Soft	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*
Medium-Soft	1.1*	1.1*	1.2*	1.1*	1.1*	1.1*	1.1*	1.1*	1.2*	1.1*	1*	1.2*
Hard-Soft	1.1*	1.1*	1.1*	1.1*	1.1*	1.1*	1.1*	1.1*	1.1*	1.1*	1*	1.1*
Soft-Medium	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*
Medium-Medium	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*
Hard-Medium	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*
Soft-Hard	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*
Medium-Hard	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*
Hard-Hard	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*	1.1*	1	1.1*
Expected Utilities	9.8	7.4	9.75	9.8	7.4	9.7	9.7	7.4	9.7	9.7	7.5	9.7
Joint Expected Utility for PM A & SUB	12.30			12.30			12.25			12.35		

At α=50% stable allocations (k=1) also begin to appear. These values represent demand of exact resources required by the PM, and allocation of resources by the SUB according to demand, respectively. These are cooperative behaviours, as opposed to the competitive behaviours expressed by values less than or greater than 1. One can also observe that the maximum overall expected utility for PM A and the SUB combined occurs when α=20% (its value is 8.75). Table 4 shows the equivalent set of results for average stability conditions. Here, α=20% appears to be sufficient to improve the behaviour, and the maximum joint expected utility (10.05) occurs at this value. Table 5 presents the results for the stable situation; no clear cut impact of the hybrid formula can be discerned. As expected, the results also clearly show that the overall utility increases as projects become more stable.

DISCUSSION AND CONCLUSIONS

A novel formula for payment to subcontractors, which shifts some of the risk for reduced productivity due to plan instability from the subcontractor to the general contractor, has been proposed. The formula requires that a price for capacity be set as well as a price for product, with a single weighting parameter to balance between them. Using a game theory based simulation, use of the formula has been shown to lead to resource allocation behaviours that benefit all parties in unstable or average conditions. The hybrid formula has impact for values of α as low as 20%.

The economic model points to additional ways to reduce variability of resource allocations, or at least reduce their detrimental effects on overall project stability. Among them: a) minimize the proportion of the labor component in any subcontract, increasing the material content; b) buffer work where the labor component of a subcontract is high; c) structure work to reduce the number of handover points between subcontractors.

Naturally, it is not only plan reliability that affects subcontractors' resource allocation decisions. There are additional factors, some of which are beyond the control of any individual project manager. The degree of demand for a subcontractor's resources in the market will impact their reliability, as will the subcontractor's cash flow and liquidity. Knowledge of the factors at work in a subcontractor's economic environment beyond the borders of a project manager's specific project may provide additional leverage for improving reliability. For example, payment terms may be more important to a subcontractor than the price for their work if they function under cash flow constraints.

Nevertheless, the advantage of the proposed remuneration formula is that it modifies behaviour directly by adjusting the basic economic incentives, assigning the risk of plan instability to the participants more closely according to their ability to reduce that risk. It should also create an environment more conducive to considerations of work flow, and facilitate application of lean construction techniques.

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