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of the Firm

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Project Work Uncertainties and the Boundaries of the Firm

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Abstract

The effective use of resources in an economy requires both that they are available where and when most needed and that they are kept employed as fully and effectively as possible. A lack of certainty over future resource needs within firms brings these two requirements into conflict. It is argued that the firm and the market offer alternative means of handling this trade-off. The market switches resource services between customers to keep specialist resources employed. However, this does not guarantee the firm that a resource will always be available when needed. The firm may therefore internalise resources, switching them between different tasks to keep them employed and to make their specialist capabilities available where most needed. Idiosyncratic advantages form an important part of the theory, often severely exacerbating resource availability issues. A model of resource planning in a project with uncertain task durations is presented to illustrate the problem faced by the firm.

1. Introduction

Because a project is a unique programme of work it involves uncertainty. Project types differ widely from routine construction projects through to blue sky research and development. Much professional and managerial work is also project based. Different types of projects involve different levels and types of uncertainty (Shenhar, 2001). Due to uncertainty the length of time that a project task will take and its exact resource needs can only be estimated ex ante. In addition, the time at which a task can begin often depends on the completion times of previous tasks, and so is subject to

uncertainty over their durations. If resources are not available when needed then substantial costly delays can result (Hameri and Heikkila, 2002).

The question asked in this paper is when different tasks will be integrated within the same firm, irrespective of whether or not that firm carries out those tasks as a supplier to a client firm, in the sense of being undertaken by resources controlled by that firm. At one extreme a project firm might be quite small in terms of the resources directly under its control, perhaps with one firm acting as a specialist project manager bringing together the activities of numerous highly specialised supplier firms. At the other the project firm might be a substantial integrated organisation, carrying out most parts of each project itself. It is not simply a 'do internally or buy' decision, however. It is also a matter of the range of tasks that are integrated within each supplier. Each supplier may be specialised in individual tasks or carry out a range of related tasks.

Sometimes tasks are consolidated to a major degree in the sense that the same set of resources sees through large parts of a project, performing multiple tasks in sequence. For instance, general construction labourers could be used to construct a building, moving on to the next task as each is finished. Alternatively, different specialist suppliers might be used to lay the foundations, build the walls, install the electrics, and so on. Clearly, a lot depends on the technologies being used in a project, and how these affect the degree to which specialists are required for each task.

Sometimes resources will be kept busy in other tasks and switched into a particular task through the use of internal authority when the need to do so becomes pressing. Resources might be brought in from other parts of the project or from other parts of

the firm. In other cases different specialist resources will be needed for each task and there will be little choice but to procure them through the market.

If:

- a particular type of resource's specialist services are likely to be time-critical
- there is considerable uncertainty about the timings of the needs for the specialist services of the resource
- there is significant scope for the resource to be used in a sequence of consolidated tasks, or good use of the resource can be made in short or less time-critical tasks while waiting for the more urgent requirement for them in the relevant project task to arise
- there is a significant variance in market demand for the resource type

then there may be a strong case for the resource to be hired by the firm for some time prior to the carrying out of the project task. It is not a big jump from this argument to see that a firm could have an incentive to maintain a pool of resources needed to carry out a range of related tasks, reallocating them across different tasks and projects as the need arises. Hence resources are used in a more multi-purpose way than would happen if each were sourced externally. While a sudden switch to such behaviour by a significant number of firms might push up the price of a resource with a particular capability significantly, greater elasticity of supply in the longer-run will tend to avert this. For instance, more workers will train to gain the skills necessary to undertake a particular type of task if there is greater demand for workers with those skills due to firms using them in a wider range of tasks.

Economists currently seem to have directed relatively little attention specifically to project-based work. This is despite the fact that it accounts for a considerable portion of economic activity. Further, it has been claimed that an increasing proportion of work is project-based in modern economies (Marsden, 2004; Whiteley, 2006), and that this has affected labour markets.

For instance, a stream of literature has focused on the need to vertically integrate in order to obtain security of supply. However, this is analysed in terms of demand variability for a product. Lieberman (1991) finds empirical support for the model of Carlton (1979), based on the hypothesis that the firm is more likely to integrate when other buyers of an input have high demand variability. According to Carlton, vertical integration is often linked to certainty of supply by both researchers and business people (see also Bolton and Whinston, 1993). Carlton notes that prices do not adjust continuously as they need to be fixed for some time to act as effective signals. In addition, firms make production decisions before observing demand and so risk having either unused or insufficient capacity. Firms compete on both price and the probability of being able to supply any individual customer. In Carlton's model firms have an incentive to partially integrate, producing for their 'high probability' demand, and purchasing through the market when they face demand over this level.

With project-based work matters are different. It is a key problem in project management to secure resources when they are needed. However, uncertainty within the project itself, rather than over the quantity of a product demanded can be considered to be the central problem in this. Resources can be booked some time in

advance to ensure that they are available when they are scheduled to be used, but this involves the problem of uncertainty over the project schedule. Actual resource need timings will deviate from those scheduled. Hence the project manager may book resources over wider time periods in order to increase the odds of having them available when needed. However, in order to save costs, some risk of a delay in obtaining resources will still often have to be borne, as will be seen later. A lack of certainty that resources will be available at the times promised by suppliers provides a further incentive to book them earlier than they are expected to be needed (Yeo and Ning, 2006).

One of the tenets of literature on the boundaries of the firm is that, but for bounded rationality, in the presence of uncertainty, the use of contingent claims contracting would obviate the need for activities to be carried out within firms. The economy would co-ordinate efficiently through the market mechanism, as in the Arrow-Debreu general equilibrium model, so that the issue of the boundaries of the firm would not arise (Dunn 2000; Foss et al., 1998). Assuming bounded rationality, the literature has put most focus on the roles of a combination of opportunism and transaction specific assets in leading to internalisation (Holtstrom and Roberts, 1998). There are also various theories of vertical integration (Casson, 1984).

In project-based work the scheduling of resource use is an important response to the costs, cognitive limits, communication imperfections, and fundamental uncertainty that make an efficient and comprehensive economy-wide contingent claims solution to resource allocation impossible in practise. Scheduling and pre-booking of resource time is necessary as a co-ordination mechanism.

Scheduling and booking resources early on acts as a check that they will be available when they are planned to be used. If any are found not to be available then it can be much cheaper to then delay or re-plan the project in order to avoid resource need clashes than to do so later on. There will often be much more freedom to put off or do without the use of a resource before a project starts than when it is already a significant part of the way towards completion. Sometimes the start of a project might be delayed for a while without incurring great costs. However, once a significant part of the costs of a project have been sunk, the net benefit of completing it can become very high. Hence completion becomes very urgent and the cost of delaying it in order to wait for resources is high. In addition, when the project is underway a lack of resource availability may cause delays leading to bookings for resources for later, dependant tasks to be missed. A lack of availability of a resource may also mean that other resources that have been booked to work jointly with it lie idle. Further, a design might be changed ex ante to use different technologies, so that a need for resources needed to work with particular technologies could be avoided. However, once a design has been partly implemented and relevant resources booked it can become much more costly to change it in order to avoid difficulties in obtaining any particular resource.

So a lack of availability of a resource when needed can therefore come to cause very high costs. Scheduling and pre-booking help different firms, or different projects and activities within a firm to avoid later having an urgent need for the same resource at the same time. They also allow suppliers of resource services to coordinate their work for different customers in order to reduce idle time between each resource finishing

work for one customer and starting work for another. These factors are of most importance when the markets for any of the resources concerned are small. In a market that is large and in which different firms' resources are readily substituted the law of large numbers reduces the odds that any particular firm will not be able to find suppliers at any given time. However, a market that is initially large may effectively be reduced to a single supplier once it has become involved in a project, as there may be significant costs involved in then switching to other suppliers. Such costs may be high, for instance, where staff have gained idiosyncratic knowledge, the supplier's proprietary technology has been integrated into the project, and where it is difficult to assess the performance of a supplier on a task that has been part completed by another supplier. The more unique a project, the greater the importance that idiosyncratic project knowledge is likely to have and also the greater the level of uncertainty the project is likely to involve. However, risks to a schedule such as bad weather or illness can affect almost any type of project.

Unfortunately, the use of scheduling and pre-booking as a co-ordination mechanism is partly frustrated for projects involving significant levels of uncertainty. In the absence of uncertainty schedules could be adjusted before projects began in order to eliminate clashes in resource use timings. With uncertainty different projects may have significant clashes in their resource needs as task timings and resource needs turn out to fail to correspond to those scheduled.

Resources urgently needed by some firms may end up being employed in less time-critical tasks in other firms. In markets that work through the forward booking of resource services, a customer for a resource can gain the use of its services simply by

booking it early, rather than because it would be willing to pay a higher price for them at the time of use. Further, uncertainty over the timings of the use of a resource reduces what a firm will be willing to pay to reserve it for a particular time period. As that time draws closer, however, the price that it will be willing to pay will change. So the firm willing to outbid others to book a resource for a particular future time period will not necessarily be the one that would have been willing to outbid other firms if the uncertainty could have been resolved beforehand. A firm that ends up with an urgent requirement for a resource at short notice therefore faces the danger of having to wait for it to become available. Resource prices that are inflexible in the short-run (Zbaracki et al., 2004) and existing contracts then create a barrier to efficient allocation, while commitments made by a firm after it has booked a resource, such as booking other resources, may significantly lock it into using it during a particular time period. If a firm waits too long before booking a resource it may therefore find it cannot later outbid other firms for its services at a particular time.

The firm may therefore choose to employ (Simon, 1951) or purchase a resource instead of procuring its services through market transactions. This helps to ensure that its specialist services are available when needed, while allowing the firm to make use of it in other tasks in the meantime. In the model that follows integration is therefore a result of scheduling problems. While this need not necessarily involve opportunism, the costs in the model resulting from scheduling problems could be partly interpreted as bargaining costs involved in resource reallocations. It is clearly the case that ex post haggling often plays an important part in relationships between firms undertaking projects. For instance, haggling may take place after part of a project has gone behind schedule and over budget over exactly where responsibility lies and what penalties or

payments should ensue. It may be unclear to what extent the over-runs were caused by the way in which previous work in the project was undertaken, by changes to the specification of what was to be done made by the client firm, or by the performance of the firm undertaking that part of the project.

While it seems clear that a combination of transaction specific assets and opportunism play an important role in integration decisions (Shelanski and Klein, 1995; Geyskens et al., 2006), the extent to which other factors lead to the integration of project-based work is less clear. As will be shown by the model, scheduling issues may lead to integration, independent of the existence of transaction specific assets and opportunism, though scheduling problems can themselves be greatly exacerbated by idiosyncratic supplier advantages. Some research on the outsourcing of project tasks has shown the importance of small numbers of potential suppliers in firm boundary choices (Pisano, 1990). This paper therefore suggests a need for further work to examine in more detail how small numbers of potential suppliers, or a small overall market size, affect integration decisions in project-based work.

Note that task and resource scheduling in projects are the basis of major bodies of research. However, according to Turnquist and Nozick (2003), despite the literature on resource-constrained project scheduling being huge, surprisingly little of it considers uncertainty. Herroelen and Leus (2005) review methods of project scheduling under uncertainty, including the use of resource flow networks in cases where resources are restricted (Deblaere et al., 2007).

Project plans commonly allow for task duration uncertainty. For instance, the PERT method (Williams, 1995) estimates a task duration using a mixture of what are perceived as the shortest time that it is likely to take, the most likely time, and the longest time. However, while this provides a way of estimating task durations, though one with some well recognised flaws, it does not fully deal with the problem of the timings of resource needs. In particular, it does not incorporate uncertainty over when the task can start (Ribera et al., 2003).

2. A model

This section models the problem of reserving resources for interdependent tasks with uncertain durations and options for integration. While putting resources together to carry out a programme of work can be a difficult task in its own right, when plans are likely to be disrupted due to uncertainties over task durations resource constraints become a serious problem.

The core of the model demonstrates the costs of resource booking uncertainties. The model then goes on to consider how these can be addressed through two alternative integration strategies. With the first strategy, task consolidation, a single set of resources performs multiple dependant tasks in sequence (Rummel et al., 2005).

Hence, when one task finishes the resources to perform the next task are always immediately available and never lie idle while waiting for the previous task to finish.

With the second strategy, dynamic resource reallocation, the resources needed to undertake a task are transferred from other tasks within the firm as needed. Such tasks might be short and so allow quick movement to the new task once they have finished

or their completion might simply be less time-critical. In addition, the resources might be replaced in the other tasks by resources easier to obtain through the market at short notice. So the necessary resources are kept gainfully employed within the firm but are also available for use in the project as required.

The trade-off between resource availability and idleness is illustrated by considering a simple case. Assume that there are two tasks to be performed in a project, each of which has an uncertain duration. Task A has to be performed first and Task B can only be started once Task A has been completed. Each task has a minimum duration and also takes an extra amount of time that is uniformly distributed. The extra amount of time is distributed between 0 and h_A for Task A, and between 0 and h_B for Task B.

It is assumed that resources freely available within the firm perform Task A, while Task B has to be performed with resources that have constrained availability and are obtained through the market. The resources for Task B can be freely booked in advance of the start of the project, but extra resource time is more difficult to obtain later on at shorter notice. It is assumed that if Task B resources have not been booked to be available to start immediately following the actual completion time of Task A then an extra cost H is incurred per time period caused by delaying the project. If Task B is not completed within the initially booked resource time then the completion of the project is delayed while waiting for additional resource time, incurring an extra expected cost D . In addition, resource costs higher than those that might have been incurred result when resources stand idle following the completion of their task or when Task B resources stand idle waiting for Task A to finish.

The starting time of the initial booking of resources for Task B, measured from the end of the minimum time needed to complete Task A, is denoted S . The duration for which the resources are initially booked, beyond the minimum time to complete the task, m , is denoted T . The cost of Task B resources per time period is w . The actual times, beyond the minima, taken to complete Tasks A and B are denoted t_A and t_B respectively.

The equations that follow consider the extra costs compared to those that would be incurred if the resources needed to perform Task B were booked to be available starting immediately following the actual time of completion of Task A, and the initial booking of resources for Task B was for exactly the duration that turned out to be needed to complete it.

First consider the expected value, l_1 , of the extra cost incurred if Task B resources are left idle while Task A is still being completed ($t_A > S$).

$$l_1 = \int_S^{h_A} \frac{w}{h_A} (t_A - S) dt_A = \frac{w}{2h_A} (S - h_A)^2 \quad (1)$$

Next consider the expected value, l_2 , of the extra cost incurred if the resource time initially booked for Task B turns out not to be long enough. This is the cost D multiplied by the probability that it is incurred.

$$l_2 = D \left(1 - \int_S^{h_A} \int_0^{T+S-t_A} \frac{1}{h_A h_B} dt_B dt_A - \int_0^S \int_0^T \frac{1}{h_A h_B} dt_B dt_A \right) \quad (2.1)$$

$$= D \left(\frac{1}{2h_A h_B} (S - h_A)(S + 2T - h_A) - \frac{ST}{h_A h_B} + 1 \right) \quad (2.2)$$

Next consider the expected cost, l_3 , of resources left unused because they have been booked beyond the time at which Task B is completed.

$$l_3 = w \int_0^S \int_0^T \frac{T - t_B}{h_A h_B} dt_B dt_A + w \int_S^{h_A} \int_0^{T+S-t_A} \frac{T - t_B + S - t_A}{h_A h_B} dt_B dt_A \quad (3.1)$$

$$= \frac{ST^2 w}{2h_A h_B} - \frac{w}{6h_A h_B} (S - h_A)(S^2 + 3ST - 2Sh_A + 3T^2 - 3Th_A + h_A^2) \quad (3.2)$$

Finally, consider the expected cost, l_4 , resulting when Task A is completed some time before the start of the booking for resources for Task B ($S > t_A$). This is the cost H multiplied by the average period of the time gap between the end of Task A and the start of the booking of Task B resources.

$$l_4 = \int_0^S \frac{H(S - t_A)}{h_A} dt_A = H \frac{S^2}{2h_A} \quad (4)$$

The overall expected value, X , of the additional costs is:

$$X = l_1 + l_2 + l_3 + l_4 \quad (5)$$

Differentiating X with respect to T gives:

$$\frac{dX}{dT} = -\frac{1}{2h_A h_B} (S^2 w + 2Dh_A + h_A^2 w - 2Sh_A w - 2Th_A w) \quad (6)$$

Setting this equal to zero gives the optimal value of T in terms of S .

$$T(S) = \frac{S^2}{2h_A} + \frac{D}{w} + \frac{h_A}{2} - S \quad (7)$$

Note that a higher value of D relative to the resource cost, w , leads to an increased value of T . Where the booking for Task B resources starts at the latest time that Task A might be completed ($S=h_A$; $H=0$), T is equal to D/w . As S drops below h_A , the value of T rises ($dT/dS=S/h_A-1$). This is because some of the time for which Task B resources are booked could result in idleness while waiting for Task A to be completed. If S drops by an amount v below h_A then the rise in T is:

$$\Delta T = T(h_A - v) - T(h_A) = \frac{v^2}{2h_A} \quad (8)$$

Similarly, the optimal value of S is defined by the following equation, obtained by substituting the above value of T into X and then differentiating it with respect to S :

$$\frac{S^3}{2} - S^2 h_A + \frac{S}{2} h_A^2 - S h_A h_B \left(1 + \frac{H}{w}\right) + h_A^2 h_B = 0 \quad (9)$$

Note that the optimal value of S depends on the value of H relative to the resource cost, w . Where H is zero, the optimal value of S is equal to h_A . Higher values of H lead to earlier values of S . This creates a risk that Task B resources will be kept idle while waiting for Task A to be completed. Hence the optimal S depends also on the levels of uncertainty over the time taken to complete both Tasks A and B, as reflected in the values of h_A and h_B .

Figure 1 provides an illustration of solutions to Equation 9. It plots the left-hand side of the equation for various values of H . w is normalised to 1.0. The values of h_A and h_B are both 2.0. The roots of Equation 9 are shown where each curve cuts the horizontal axis. It can be seen that there are three real roots in each case. However, only the middle root, which lies between 0 and h_A , is relevant. It can be seen therefore that the optimal value of S falls at a decreasing rate as the value of H increases (note that as S falls there is an increasing expected idleness cost of any further reductions in S).

The expected demand for Task B resources, Y , is the initially booked time plus the expected value of any extra time that might be needed to complete the task:

$$Y = T + \int_S^{h_A} \int_{T+S-t_A}^{h_B} \frac{t_B - T - S + t_A}{h_A h_B} dt_B dt_A + \int_0^S \int_T^{h_B} \frac{t_B - T}{h_A h_B} dt_B dt_A \quad (10)$$

The variance of the demand for Task B resources is:

$$\begin{aligned} & \int_S^{h_A} \int_{T+S-t_A}^{h_B} \left(\frac{t_B + t_A - S - Y}{h_A h_B} \right)^2 dt_B dt_A + \int_S^{h_A} \int_0^{T+S-t_A} \frac{(T - Y)^2}{h_A h_B} dt_B dt_A \\ & + \int_0^S \int_0^T \frac{(T - Y)^2}{h_A h_B} dt_B dt_A + \int_0^S \int_T^{h_B} \frac{(t_B - Y)^2}{h_A h_B} dt_B dt_A \end{aligned} \quad (11)$$

The variance is decreasing in D . Increasing values of D lead to increasing values of T , while not affecting S (Equations 7 and 9), so making it less likely that the initially booked resource time turns out to be insufficient (Y , T , and h_B all become closer in value). However, this security comes at the expense of having additional expected resource idle time. It can be seen from Equations 7 and 9 that higher values of H increase the variance. They lead to the resources for Task B being booked earlier (a fall in S), increasing the chance that they will stand idle waiting for Task A to be completed. T increases to compensate, but not by as large an amount as the fall in S

($0 < S < h_A$; $-1 < dT/dS < 0$). As S falls by an amount v below h_A the expected idleness of Task B resources while waiting for Task A to finish is in fact:

$$\int_{h_A-v}^{h_A} \frac{t_A - h_A + v}{h_A} dt_A = \frac{v^2}{2h_A} \quad (12)$$

This is the same as the increase in the period over which Task B resources are booked (Equation 8). So a fall in S results in an increase in T that exactly covers the extra expected idleness of Task B resources. The variance of actual idleness around this therefore adds to the overall uncertainty of the project schedule.

Now consider the case of the integration of both tasks within the same firm, whether within a client firm or supplier, where they are undertaken by the same set of resources (task consolidation). Task A resources also undertake Task B. Once they have finished Task A they are then immediately available to undertake Task B. For simplicity, they are assumed to be available for as long as needed to finish the task before they are moved on to other tasks within the firm. In order to avoid duplication in the model, it is assumed that, while Task A resources are capable of undertaking Task B, specialist Task B resources are incapable of undertaking Task A. Task A cannot be performed to any acceptable standard without the capabilities of specialist resources.

The opportunity cost of Task A resources to the firm per time period is denoted c_A . The opportunity cost depends on a number of factors. One is the urgency of other tasks for which the resources are needed. This is partly determined by the availability

of alternative resources to undertake those other tasks. Another factor is the degree of specificity of the resources to Task A: the degree to which they are intrinsically of lower value in alternative tasks. For simplicity, it is assumed that the distribution of the duration of the Task B is unchanged, but it is also assumed that the task may be completed to a different standard, giving a change in the value of the project of R . The value of R may reflect knowledge advantages of having the same labour undertake both Tasks A and B, the use of resources of a different standard, the elimination of other types of handover costs, and a loss of specialisation advantages in a single task. The change in the expected project value is:

$$\begin{aligned}
 & R + X - (c_A - w) \left(m + \int_0^{h_B} \frac{t_B}{h_B} dt_B \right) \\
 & = R + X - (c_A - w) \left(m + \frac{h_B}{2} \right)
 \end{aligned} \tag{13}$$

Now consider a further possibility for the integration of Task B with other types of task: dynamic resource reallocation. This is where specialist Task B resources are used in other activities within the firm between times when they carry out tasks that require their specialist services. Assume that the cost of the resources being supplanted in the other activities per time period is w_2 . There is a chance that the Task B resources will be busy in other, more urgent tasks within the firm when required and hence there is an extra expected cost l_{42} analogous to l_4 above. V is the difference in the value of all the tasks performed by Task B resources resulting from using the strategy. There may be a loss of task specialisation advantages, but it is also possible that Task B resources have higher capabilities across all the tasks. Switching resources out of them into Task B may also cause some level of expected disruption

cost to those tasks. i_B is the expected time between the last specialist need for Task B resources within the firm and the start of Task B in the current project. The change in the expected value if the resources are retained within the firm between the previous need for their specialist services and the start of Task B is therefore:

$$X - l_{42} + V - i_B(w - w_2) \quad (14)$$

If either Expression 13 or 14 is positive then integration is preferred.

A firm taking part in a project may therefore carry out a range of project tasks requiring similar resource types, using task consolidation where the tasks are serially dependent and dynamic reallocation of resources where they are not. Knowledge advantages form an important part of the logic of such strategies.

Note that a further possible source of uncertainty over resource needs is where information gained during the execution of Task B could lead to some reworking of Task A before Task B is completed. However, possible iterations within subtasks of Tasks A and B could be considered part of the cause of uncertainty over their durations.

3. Discussion

In the model the uncertainty of the durations of Tasks A and B creates extra costs in carrying out Task B in two different ways. Firstly, it can lead to idle resources. Secondly, it leads to costs when resources are not available when needed. These two

types of cost have to be traded off against each other. While one may largely dominate the other in scheduling decisions, the costs that are incurred may nevertheless be substantial. For instance, project delays could be extremely costly so that a lot of slack is built into resource bookings, but this is not to say that the extra resource costs are necessarily small.

The costs of not having a resource needed to undertake a task in place at the right time will be affected by a range of factors:

- The number of different resources that are needed: this is a crucial factor as the more that are needed the more difficult it will tend to be to quickly gain the services of the full set of required resources. This creates an incentive to internalise the full sets of resources required to complete specific types of task. External sourcing of a single resource may put the usefulness of a whole set of other resources in jeopardy unless the costs of booking over a wide time period are incurred
- There may be an urgent need for the output of the project, and the task may be on the critical path
- A large part of the cost of the project may have already been incurred, so creating a strong incentive to generate rapid returns, unless the expected value of the output of the project has also dropped significantly, or the expected value of remaining costs has increased.
- The timings of the gaining of information indicating delays in or the likely early completion of each task are important. The later it is gained and shared, the less time there is available to gain additional resource time or to reallocate booked resources

- The cost of switching to new resources if the current resource is unavailable beyond the time initially booked: this includes both the cost of losing idiosyncratic advantages, such as the project knowledge of workers, and the costs of searching for and deploying fresh resources (plus other types of transaction costs where the resource services are sourced outside the firm)
- The chances that the supplier (whether internal or external to the firm) of a resource will be able and willing to redeploy it to alternative uses at late notice in order to reduce its idle time
- The variance in market demand for the resource type
- The size of the market for the resource type: if the market is large then the law of large numbers will tend to even out demand fluctuations from individual firms, except for those that are caused by factors common to many customers. There will then be less incentive to book it far in advance.
- The suitability of substitute resource types: if alternative resource types are close substitutes, then there is more chance of suitable resources being available as and when needed, though search costs may still be significant
- Locality: if local resources have strong advantages, through lower 'economic distance' this effectively reduces the size of the market for superior resources sharply unless the local market is itself large (as may be the case if the firm locates itself in an industrial cluster)
- Suppliers without previous dealings with the firm may be less suitable.

The market keeps resources employed by switching them between different customers, though with the problems of variations in demand and the presence of transaction costs. If demand is large enough then the advantages of a highly

specialised resource can be gained. As a resource type becomes more specialised, the narrower is the market that it serves, and hence the greater the chance that resources will be in excess supply at any particular time. This increases the charges that they have to make in order to cover their opportunity costs of being in the market. Conversely, it also increases the odds that they will be in excess demand at any time and so unavailable to some firms.

The net value of an internalised resource depends on its degree of specialisation, which partly determines its cost, and also the frequencies with which the tasks for which it is most suited take place within the firm. Often the services of a more specialised resource will cost more, and there will be a greater opportunity cost to employing it in tasks outside its direct specialisation. The internalisation of a resource that is needed for a task will be more effective when there is a resource type available that has a relatively high net value within the task, but is also not highly task-specific. Here 'task-specificity' is defined in terms of the net value of the resource in alternative tasks to which it can be diverted within the firm relative the net value of the resources it supplants in those tasks. The firm may employ a less specialised resource than it would use through the market in order to gain lower levels of task specificity. Task specificity is more important the more patchy the firm's need for the specialist aspect of the resource's capabilities.

The design architecture involved in a project may also be endogenous. In the model the resource-scheduling problem was partly created by the interdependence between the two tasks. Reducing such interdependencies therefore reduces the costs resulting from resource constraints. This can be achieved through a modular architecture with

loose coupling between modules. A further way of reducing resourcing uncertainties for a task is to reduce the level of uncertainty surrounding preceding tasks on which the task is dependant. One way of achieving this is to use well-understood technologies, or to reuse old designs (Nightingale, 2000).

Uncertainty can also be reduced through investment early on in a project (ibid). More effort can be put into understanding customer requirements, and in verifying designs and new technologies. For instance, methods such as simulation and physical prototyping help in gaining information early on. Thomke and Reinersten (1998), however, suggest that development flexibility can substitute to some extent for early information gathering. With such a strategy, the firm maintains options to respond to information that is gained later on in a project.

The firm can also attempt to improve the management of the interfaces between project tasks. Hameri and Heikkila (2002) provide evidence suggesting that the improved management of task interfaces, including the dynamic movement of resources between tasks that is facilitated by achieving greater monitoring and sharing of information about task progress, can significantly reduce the problem.

4. Conclusion

A model was presented which demonstrated how uncertainty and resource constraints in a project combine to lead to a lack of availability or idleness of resources, and how this can lead to integration. It also demonstrated the optimisation problem for resource bookings in a project. A number of further endogenous factors were discussed. These

included the management of task interfaces (at which major delays can occur), architectural choices, the possible reduction of uncertainty through the reused of old designs, the use of well understood technologies, and investments in uncertainty resolution early on in a project.

While one view is that resources are internalised in the firm due to opportunism and transaction specific assets, in this paper it has been argued that internalisation may also result from the fact that in some cases the firm will more effectively handle the trade-off between resource availability and usage than the market. When transacting for resource services through the market, the firm faces the problem that the resources may simply not be available when needed. In the model the firm trades off the costs of idle resources and lack of availability against each other, and uses internalised resources where appropriate to reduce those costs.

While the market can achieve high resource usage by switching resources between customers, the firm can do so by consolidating tasks and by switching resources between tasks, prioritising those in which they are of higher value at any time, such in as those that are time-critical. The effectiveness of the internalisation of a resource depends both on how often its specialist services are needed by the firm within a particular task and on its level of task specificity within the firm. The effectiveness of a specialised market depends on its size. In both cases there is a trade-off between effective resource usage and the degree of specialisation of the resource. Knowledge advantages may result as a resource is switched between different tasks within the firm rather than being specialised in a single type of task and instead switched between different firms. Idiosyncratic resource advantages reduce the effective market

size faced by the firm, so making it more likely that the resource will not be available when needed if its services are procured from suppliers specialised in narrow tasks.

Finally, it should also be recognised that unpredictable needs for resources, such as to deal with urgent problems that might arise unexpectedly within the firm, are a further reason for the firm to internalise resources in order to dynamically allocate them to tasks rather than relying on availability of those resources in the market as and when needed.

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Figure 1

The Starting Times for Task B Resource Bookings for Different Values of the Cost H

