The Impact of Engineering Design on Outsourcing Decisions

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ABSTRACT
Many models in the literature examine outsourcing based on product modularity; however, modularity is assumed to be known and exogenous. In reality, modularity is a decision variable defined (i.e. built into the product) during the engineering design phase of the product development (PD) process. This paper bridges the gap between the outsourcing literature and the engineering design literature by incorporating into the outsourcing decision model detailed engineering design information regarding the time spent on various engineering design activities within the PD process (e.g., system design, detailed design, and testing and integration).

In this paper, a mathematical model is developed to study the impact of outsourcing and time spent in the various engineering design activities on firm's revenue (represented by a marketing window) for different PD scenarios. These scenarios differ in four major factors: technological capability of the firm and its suppliers, design task size and complexity, nature of detailed design work (i.e., fraction of rework), and amount of outsourcing. It is shown that this model is a convex optimization problem that admits a global optimum; however, no explicit closed-form solution could be obtained and the problem was solved using optimization software.

The optimal solution reveals several interesting managerial insights regarding the impact of the various engineering design decisions on the outsourcing decision. First, spending more time in system design leads to higher outsourcing fraction and vice versa; that is, well defined product architectures lead to higher outsourcing. Second, higher firm capability makes outsourcing less attractive. Third, outsourcing is found to be more attractive at the medium task sizes compared to larger or smaller tasks. Fourth, a product with a complex architecture will lead the firm to spend more time in system design and thus outsource more. Lastly, as the rework fraction of detailed design increases, it is better to spend more time in system design and outsource more.

(Keywords: outsourcing decision, product design & development, engineering design, modularity, product complexity, task size, firm capability).

NOMENCALTURE

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T_{total} : Product life cycle. Total time for the whole process [unit time]

T_d^o : Nominal time spent in detailed design [unit time]

$T_{d\,OEM}^o$: Detailed design duration for OEM, including all rework

$T_{d\,Supplier}^o$: Detailed design duration for Supplier, including all rework

T_S : Time spent in system design [unit time]

T_m : Marketing window

P_{OEM} : Success probability forthe OEM at testing and Integration

$P_{Supplier}$: Success probability forthe OEM at testing and Integration

α : Fration of rework [%]

γ : Shape parameter for product complexity in system design [$\gamma \geq 0$]

λ : Task size at detailed design phase [unit time]

μ : OEM (Firm) capability [$\mu \geq 1$]

$\bar{\mu}$: Modified OEM capability

ν : Information gap between OEM and Supplier

ε: Outsourcing fraction[$\varepsilon \geq 0$]

G: Product generations

1. Introduction

The aggressive nature of competition in today's markets makes product development (PD) a central point of contest. The benefit goes to the companies that are able to efficiently introduce new products into the market. These firms guide their development effort toward three main objectives: low price, high quality, and long marketing window. Although these objectives are often clashing or conflicting, they must be compromised using an optimal PD process.

The product development (PD) process is a sequence of all the essential tasks that a firm must perform to develop, manufacture and sell a product (Ulrich and Eppinger, 2004). These tasks include marketing research (where customer needs are identified and product attributes are specified), system design (which includes product architecture definition, subsystem identification and interfaces), engineering design (also referred to as detailed design and includes fully specifying the product dimensions, tolerances, and material), prototyping (which includes product validation and testing), manufacturing planning (which includes process design for ramp-up and full production), and supply chain design (which may involve a large number of suppliers).

Outsourcing plays a significant role within the above product development process. Firms outsource for various reason. The main reason is simply cost considerations. Generally, buying components from a supplier costs less than making them in-house. Another driving force is capacity. Sometimes an Original Equipment Manufacturer (OEM) does not have enough production capacity to make a component or product. Lack of knowledge, expertise, or even quality, could be another motive for outsourcing. Additionally, firms tend to outsource noncore (or noncritical) components or subsystems that either have low influence or impact on product performance (or quality), which may be critical to the marketability or image of the product, or that do not constitute a core competence for OEM's long-term survivability and competitiveness.

Outsourcing has various other dark sides, which also make it less attractive. A major one is the loss of knowledge or basically eroding knowledge know-how for producing the outsourced components or subsystems by reducing cumulating learning-by-doing. As a result, an OEM could be trapped into outsourcing (long-term dependence on supplier for knowledge and know-how), which makes it more expensive (than what it used to be) to build the components in-house in the future. Another down side is the potential for loss of local jobs within the community, which ultimately could result in loss of market share in local markets.

The careful allocation of time and resources to various development activities, in addition to determining the right amount of outsourcing, are critical for successful and profitable product development (PD). Essentially, PD is a sequential process where various decisions in each stage are made in conjunction with both former stages and later ones. Therefore, spending more time in system design activity during PD leads to more modular products, which may in turn be more amenable to outsourcing. This makes outsourcing decisions directly related to design decisions and particularly the effort spent on each phase (or stage) of the development process (i.e., system design, detailed design, and integration). Clearly, the probability of integration failure for a modular architecture is lower than that for an integral architecture due to well defined product modules (e.g., subsystems) and the various interactions between them. However, spending less time in system design may lead to higher probability of integration failure for the outsourced modules due to the nature of product architecture and the lack of proper or ideal communication with the OEM (compared to communications between two departments within the same organization) and lack of the systems perspective that usually resides within the OEM and hard to communicate to the supplier of an outsourced module.

Few outsourcing models take into account details of the engineering design process; mainly discussing the impact of product modularity as laminated exogenous variable. In this paper, we consider detailed design process information (e.g. time spent on each design activity) in order to arrive at an optimal outsourcing strategy. Thus, our model bridges the PD process literature and the outsourcing literature into a unified model. A good PD outsourcing model should not only include time and cost considerations, but also does not ignore the loss of knowledge which affects negatively the OEM's future capability. Although, it might take years to erode design knowledge and know-how within a development organization, we consider the average of the long term capability as the OEM's current capability in order to account for this long-term loss. These various assumptions are described in details in later sections.

In this paper, a mathematical model is formulated to maximize OEM's revenues through a larger marketing window. The decision variables are the time spent in system design and outsourcing fraction. Different scenarios within the product development process will be investigated. These scenarios differ in product complexity (i.e. newness), task size (e.g., small and large), firm capability (i.e. resource levels and expertise), and nature of detailed design work. It is shown that this model is a convex optimization problem that admits a global optimum; however, no explicit closed-form solution could be obtained and the problem was solved using optimization software.

The rest of the paper is organized as follows. The relevant literature is described and discussed in the next section. In Section 3, we present the formulation for the proposed model; particularly, time spent in system design and detailed design, failure probability during systems testing and integration for both OEM and supplier, and finally marketing window and revenues. Model analysis and simulation procedures are in Section 4. Section 5 contains sensitivity analyses results and their discussion. Finally, we present our conclusions in Section 6.

2. Literature Review

2.1 Outsourcing Literature

Outsourcing decisions are critical due to their impact on the PD process (Ulrich and Ellison, 2005; Staudenmayer et al., 2005). For instance, Anderson and Parker (2002) presented a model that accounted for learning effect in make/buy decisions. However, their model captured the effect of learning for an infinite time horizon, which is generally not the case in most outsourcing scenarios. Firms switch their policy whenever they experience that outsourcing is not beneficial. Moreover, they assumed that outsourcing decisions are made once during this infinite time. It would be more realistic to study outsourcing for one generation of a product by including the effect of this decision on future capability if the OEM decides to quit outsourcing and make the component in-house.

Ülkü et al. (2005) examined how the process adoption is impacted by the make/buy decision. They argued that outsourcing does not grantee faster time-to market, which was explained by insufficient client base at the supplier. This result needs more explanation and study involving the various factors that could delay time-to-market like quality assurance. Ülkü and Schmidt (2005) found that firm capabilities play an important role in product architecture. They studied the interrelation between the degree of modularity and outsourcing the product design. Moreover, the model mainly consisted of three factors: component performance, total product performance, and market characteristic. However, the model was deterministic and did not include time allocations at the various development phases.

Another study done by Mikkola (2003) linked modularity of the product to outsourcing and firm's learning. She argued that outsourcing creates certain degree of inter-dependence. However, most of these insights regarding outsourcing were made through case observations and did not include other factors that link the interrelation between the OEM and the supplier. Along the same stream, Argyers (1996) found that OEM and supplier capabilities have a role in the outsourcing decision. This study was conducted based on observing various product development processes. Novak and Eppinger (2001) developed a statistical model to study the relation between product complexity and sourcing. Their model showed evidence of complementarity between product complexity and vertical integration. Becker and Zirpoli (2004) presented insights that linked various product development aspects (outsourcing, performance integration and product architecture). Their insights were based on an extensive ten-year data from European automotive industries. Moreover, they argued that outsourcing influences product performance.

2.2 Product Development Literature

Several studies encourage speed to market in order to achieve considerable amount of market share (Lilien and Yoon, 1990; Meyer and Utterback, 1995; Smith, 1999; Langerak and Hultink, 2006). However, this may lead to an immature new product (i.e. with lower than optimal performance or quality) which reduces product's demand and overall firm profits (Cohen et al., 1996; Bayus, 1997; Karlsson and Ahlstrom, 1999).

Bayus et al. (1997) addressed the question of when should a firm introduce a new product and what should its performance level be? They assumed that every firm in the market has the same capability and discussed the time to introduce the new product to market relative to market's leader introduction time. Bayus (1997) continued the flow by addressing normative research by relating various market, demand, and cost conditions to maximize the profit. Nevertheless, the model did not include characteristics of the product regarding its complexity.

Cohen et al. (1996) generated a mathematical model of time-to-market decision given a fixed performance level. Yet, the model was limited to constant market demand and price. Along similar lines, Calantone and Di Benedetto (2000) addressed the same tradeoff (i.e. between product performance and time-to-market) when product development phases are overlapped and jointly working towards performance improvement. This model did not include other important factors that can affect performance, such as firm capability, product complexity, and it was deterministic.

Other researchers studied PD in a stochastic manner as one major issue is the failure at testing and integration phase during PD. Morali and Soyer (2002) studied the optimal stopping in software testing. They developed a sequential decision model to find the optimal release time. Similarly, Eppinger et al. (1997) used a signal flow approach to analyze PD. The model computed PD lead-time for a probabilistic changing design environment.

3. Model Description and Formulation

We consider a typical product development process which consists of four phases or stages: system design, detailed design, testing and integration, and marketing (Ulrich and Eppinger, 2004). The process is mainly performed sequentially as shown in Figure 1. The development team first spends time to define the product architecture (i.e. specifying subsystems and their interfaces). We assume that the more time spent on system design, the less chance the product fails during testing and integration. That is, more time spent on system design results in more modular product architecture (with clear and well defined subsystem boundaries), which in turn leads to less chance of failing testing and integration.

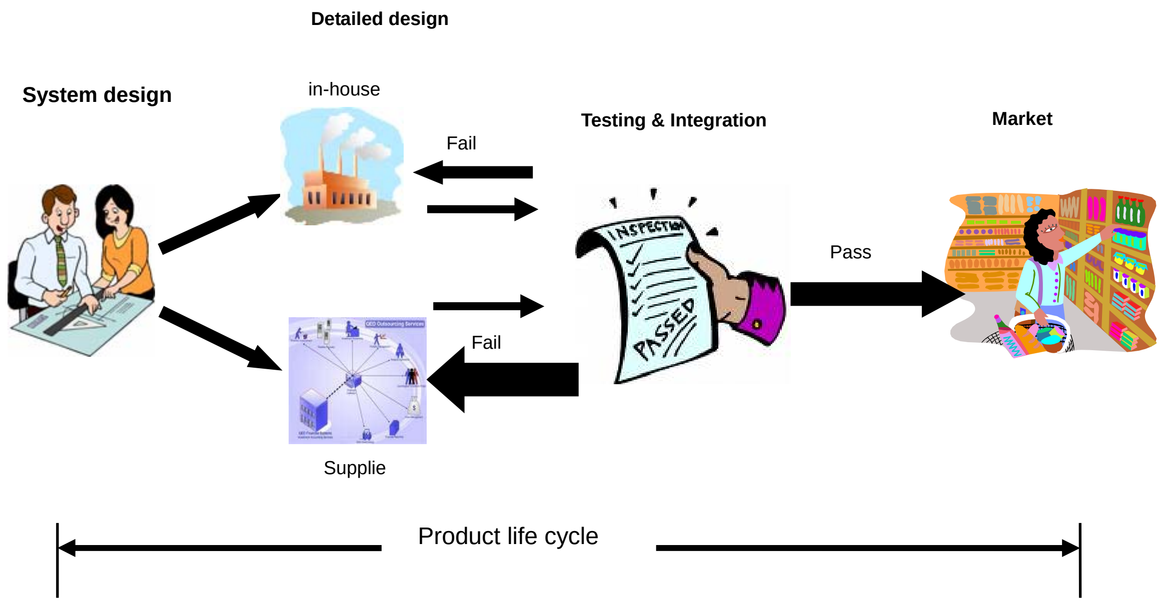

Figure 1. Product development process major phases

Once the product architecture and the various subsystems are identified, the OEM (also referred to as the 'firm') is ready to make its outsourcing decision. For any outsourcing amount, both the firm and the supplier will work concurrently on their assigned tasks consuming a nominal time which is predicated by their associated expertise. At this stage (and after performing detailed design for the first time, which consumes the nominal allocated duration) the detailed design teams (i.e., OEM and supplier) believe that they have achieved 100% quality (based on the pre-specified design requirements or specifications). However, during testing and integration, a fraction of this quality will be confirmed and hence some of the previously performed work needs to be reworked (this also called 'design iteration'). We assume that the supplier is more likely to fail at this stage due to the lack of intense communication with OEM (crossing organizational boundaries) and lack of complete information about the product or perfect specifications. In addition, we assume that design iteration takes place during detailed design phase only and do not require system redesign. The number of design iterations is related to the failure probability, which is, in turn, a function of the time spent on system design. The OEM and supplier must rework whenever they fail during testing and integration in order to achieve the required specifications and product performance before the product is launched to the market. This is a work policy assumption, which we made in our model. However, other work policies could be implemented in an extension to this model, such as working only up to a predefined maximum number of design iterations. Finally, for simplicity we normalize the product life cycle (i.e., the sum of system design time, detailed design time, and marketing window) to 1. We also assume that there exists a fixed and known marketing window beyond which there is no significant demand for the product under development.

Finally, it is worth noting that excluding the production or manufacturing stage from our hypothetical model, as shown in Figure 1, does not detract from the value of the model for two reasons. First, one can assume that this model reflects a software development process, where production (i.e. making copies of the developed software) is a relatively minor issue compared to development. Second, even for other types of products, we assume that the production stage is not impacted by any of the upstream development decisions and does not impact any downstream marketing decisions (assuming that any quality issues during production are not a result of design decisions, but rather are an intrinsic property of the existing production system).

Based on the above model description and assumptions, we, next, formulate the various mathematical constructs required for capturing the trade-off between product quality and the narrowing marketing window.

3.1 System Design Stage - Product complexity

The product development process starts with system design where the team spends T_s time units to generate the product architecture, define major subsystems and interfaces, and set target costs and specifications. We assume that the success of the product during testing and integration phase is solely determined by the amount of time spent on system design. Moreover, the supplier will generally have lower probability of integration success; however, longer times spent on system design will reduce the gap between the probabilities of success of the supplier and the OEM. Therefore, the success probability during testing and integration (*P)* is expressed as:

$$\begin{aligned} P_{OEM}(T_s) &= T_s^{\gamma} \\ P_{Supplier}(T_s) &= T_s^{\gamma+\nu} \end{aligned} \qquad (1)$$

The success probability is assumed monotonically increasing with respect to T_s. The shape parameters γ and *v* determine how fast the success probability reaches 100% and the gap between the success probabilities, respectively, as shown in Figure 2. The probability of success gap, *v,* can be seen as lack of information, communication and translation (e.g. language barrier or measurements system), or even perfect specification. Moreover, the supplier does not completely know the product architecture and its various subsystems (i.e., does not have the systems perspective than an OEM may have). Figure 2 illustrates that the supplier needs to spend more time to get to the same success probability as the OEM.

Equation (1) indicates that as T_s increases, the probability of success (*P*) raises rapidly with low values of *γ* and slowly with higher values of γ. The value of the shape parameter *γ* is determined by the complexity (or degree of newness or innovativeness) of the product from the firm's perspective (Johannessen et al., 2001). When the product is relatively complex, the firm needs to spend more time to develop the product architecture (i.e. decompose the system into modules / subsystems and define various interfaces) (Bashir and Thomson, 1999). This can be seen when the product is totally new to the firm (compared to a derivative product), firms struggle more at early stages and leads to frequent failures during testing and integration (Sethi, 2000).

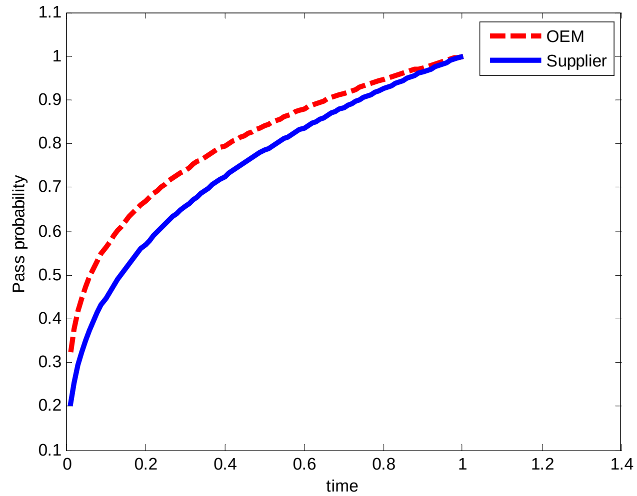

Figure 2. Success probabilities for OEM and supplier versus time in system design T_s

3.2 Detailed Design Stage - Task size and firm capability

During this phase, a complete specification of the geometry, tolerance, and material for all parts and subassemblies of the product is performed. As shown in Figure 1, the OEM decides prior to this stage what to outsource to the supplier. The OEM should outsource the right fraction ε to maximize its marketing window. The time spent on this stage is generally effected by two factors: task size and firm capability. Intuitively task size increases the duration of detailed design. However, firm capability (e.g., knowledge or expertise) reduces the duration for any task size exponentially.[1] Thus, the nominal duration of detailed design (i.e. the estimated time to be spent on detailed design, without any rework or design iteration considered) is:

$$T_d^o = \lambda^{\mu} \qquad (2)$$

Figure 3 illustrates that given any task size, then different firms with different could have different completion times depending on their capabilities. Note that the task size ranges between 0 and 1. Therefore, any task size which is closer to 0 is assumed to be very small and can be finished instantaneously. On the other hand, a task with a size close to 1 is considered to be very large and consumes the whole product life cycle in order to finish. For example, three different firms with capabilities μ=1, μ=2, and μ=3 performing a task of size λ=0.4, will complete this task in 0.4, 0.16, and 0.064 time units, respectively (see Figure 3). Also, note that a firm's capability ranges between 0 (no capability) to ∞ (extreme capability). Thus, varying task size λ and firm capability μ allows us to examine different detailed design conditions.

[1] This relation is supported by standard learning curve theory (Wright 1936).

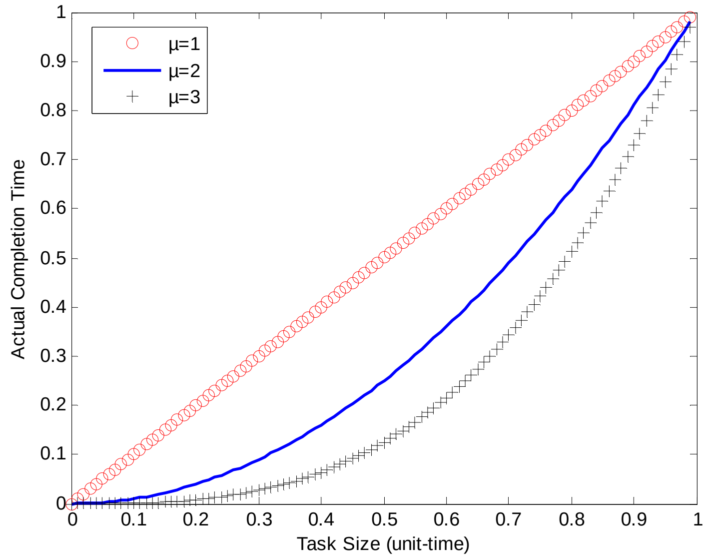

Figure 3. Nominal detailed design duration with firm capability and task size

3.3 OEM and Supplier Detailed Design Duration

The OEM and supplier work concurrently to finish their assigned detailed design work. The outsourcing fraction reduces the task size for the OEM to (1-ε) λ, where the supplier will have a task size of ελ. But the outsourcing fraction will decrease the OEM long-term development capability due to loss of knowledge and development know-how regarding the outsourced modules. Thus to model this long-term effect (of outsourcing) on current OEM capability, we perform a net present value calculation on the current capability for G^{th} generations of the product. It is reasonable to assume that current OEM capability will be obsolete after the G^{th} generation of the product. Therefore, the modified OEM capability is estimated by:

$$\overline{\mu} = \frac{1}{G}\left(\sum_{n=1}^{G} \frac{\mu}{(1+\varepsilon)^n}\right) \qquad (3)$$

In Figure 4, suppose that the OEM current capability μ=1 and the OEM outsources 50%, then the modified OEM capability is 0.2, 0.35, and 0.5 for G=10, G=5, and G=3, respectively. It is obvious that the OEM will be affected worst when G is higher because the need for knowledge is more crucial when the OEM has protracted product generations ahead; hence, the long term effect of outsourcing will be more noticeable.

Although firm capability may also increase from one generation to the next due to learning-by-doing, we present here the worst case scenario where knowledge loss due to outsourcing is more prominent. Furthermore, we assume that the supplier is initially as capable as the OEM. Finally, the nominal detailed design duration for both OEM and supplier becomes as follows:

$$\begin{aligned} T^{o}_{d\ OEM} &= \left((1-\varepsilon)\lambda\right)^{\overline{\mu}} \\ T^{o}_{d\ Supplier} &= \left(\varepsilon.\lambda\right)^{\mu} \end{aligned} \qquad (4)$$

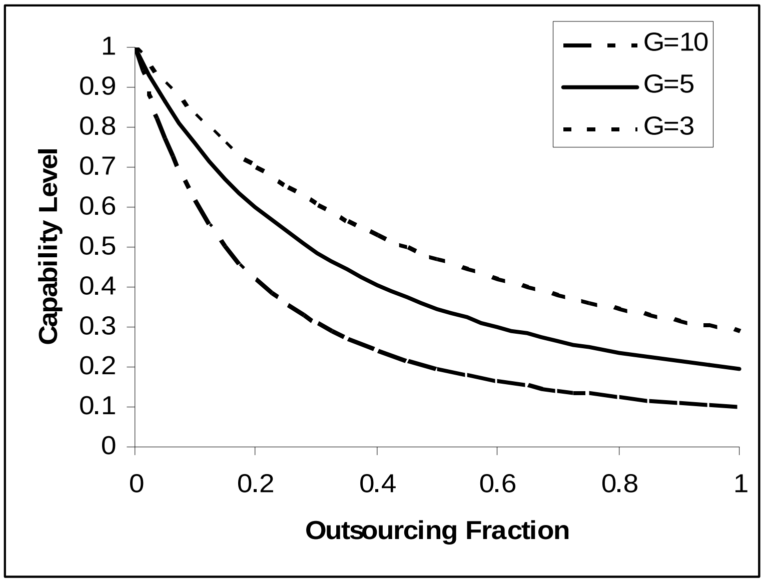

Figure 4. Outsourcing fraction effect on OEM's capability for different product generations

3.4 Testing and Integration Stage – Design iteration or rework

Once the OEM and supplier complete their assigned detailed design work, the outcome is checked during the testing and integration phase, where there is a chance that the work of the OEM, supplier, or both does not pass satisfactorily and requires modifications. The probability of success (or failure) is directly related to the time spent in system design as previously discussed. However, when failure occurs and some rework is necessary, the fraction of rework (α) depends on the nature of the detailed design (e.g. a CAD model is easier to rework than a clay model). The OEM work policy is that the product must achieve the required performance or quality prior to marketing. That is, the OEM and supplier must pass this phase in order for the product to be introduced into the market. The duration of this process is simply the maximum time spent on detailed design (including design iteration) by either the OEM or supplier. Each time the design fails, only a fraction of the prior work is approved and therefore both the OEM and supplier need to work on the remaining design issues. Although the probability of failure is constant, the amount of rework is reduced in each subsequent design iteration. Note that when the OEM or supplier fails the first time, they will spend a rework time of $\alpha\ T^o_d$. However, the second time they fail, they need to spend only $\alpha^2\ T^o_d$ and so on. Thus, the expected time that detailed design stage consumes, considering all rework to be performed (i.e. design iterations), is expressed as:[2]

$$E(T^o_{d\ OEM}) = \frac{T^o_{d\ OEM}}{1-\alpha(1-P_{OEM})}$$
$$E(T^o_{d\ \text{Supplier}}) = \frac{T^o_{d\ \text{Supplier}}}{1-\alpha(1-P_{Supplier})} \qquad (5)$$

[2] $E(T^o_{d\ OEM}) = T^o_{d\ OEM}.P_{OEM} + T^o_{d\ OEM}(1+\alpha)P_{OEM}(1-P_{OEM}) + T^o_{d\ OEM}(1+\alpha+\alpha^2)P_{OEM}(1-P_{OEM})^2 + ..$

$E(T^o_{d\ \text{Supplier}}) = T^o_{d\ \text{Supplier}}.P_{Supplier} + T^o_{d\ \text{Supplier}}(1+\alpha)P_{Supplier}(1-P_{Supplier}) + T^o_{d\ \text{Supplier}}(1+\alpha+\alpha^2)P_{Supplier}(1-P_{Supplier})^2 + ..$

Since both the OEM and the Supplier are working concurrently, the total time consumed in detailed design stage is simply $\max\{E(T^{o}_{d\,OEM}), E(T^{o}_{d\,Supplier})\}$.

3.5 Marketing Window T_m

Time-to-market plays a major role in OEM's revenues. Having a large marketing window will increase the total sales volume of the product simply because the OEM will have sufficient amount of time to sell the product. Our objective is to maximize OEM's revenues by maximizing the marketing window, T_m.[3] Thus the overall model can be summarized as a well bounded non-linear convex optimization problem as follows:

$$
\begin{aligned}
& f(T_m, T_s, \varepsilon) = \max_{T_s^*, \varepsilon^*} T_m \\
& s.t \qquad (6) \\
& T_m + T_s + \max\left[\frac{\left((1-\varepsilon)\lambda\right)^{\mu}}{1-\alpha(1-T_s^{\gamma})}, \frac{\left(\varepsilon.\lambda\right)^{\mu}}{1-\alpha(1-T_s^{\gamma+\nu})}\right] = T_{Total}
\end{aligned}
$$

4. Analysis

It is not easy to find an optimal solution analytically since it requires trial and error iterations. However, it is easier to get an analytical solution to the optimization problem in (6) for the binary outsourcing decision (i.e. ε =0 or ε =1) as described in Section 4.1; otherwise, using optimization software becomes necessary to solve Equation (6), as described in Section 4.2.

4.1 Binary Outsourcing Decision (Complete in-House or complete Outsourcing)

In some cases, the OEM makes the decision to fully outsource ε=1 or make every thing in-house ε=0. The only constraint that the problem has is time limitation. Assuming that each time the product fails at testing and integration then the detailed design team will rework the whole task (i.e. α=1). By substituting the equality constraint into the objective function then the objective function can be rewritten as:

$$f(T_s) = T_{total} - T_s - \frac{\lambda^{\mu}}{T_s^{\gamma}} \qquad (7)$$

From which the optimal time to be spent in system design given that OEM will perform the complete in-house:

$$T_s^* = \left(\gamma.\lambda^{\mu}\right)^{\frac{1}{1+\gamma}} \qquad (8)$$

When relaxing the assumption of α=1(worst case scenario), then the optimal time to be spent in system design is expressed as:

$$T_s^* \le \left(\gamma.\lambda^{\mu}\right)^{\frac{1}{1+\gamma}} \qquad (9)$$

Note that the optimal time spent in system design is an increasing function in product architecture complexity and task size. However, it is a decreasing function in firm capapbility. However, if the OEM decided to perform complete outsourcing then the optimal time spent in

[3] Generally, revenues have many key inputs such as product demand, price, and marketing window. Assuming constant demand and price, then the marketing window becomes a good proxy for revenues.

system design is shown in Equation (10), which indicates that when both OEM and the supplier has the same capability then it is optimal to spend more time in system design when the OEM has to outsource 100%.

$$T_s^* \le \left((\gamma+\nu).\lambda^{\mu}\right)^{\frac{1}{1+\gamma+\nu}} \quad (10)$$

4.2 Partial Outsourcing (0< ε <1)

In this kind of outsourcing the OEM must outsource the right amount in order to maximize the marketing window. Our objective is study to the influence of the various model parameters on the optimal time in system design and outsourcing amount. It is not easy to get an analytical closed-form solution to the optimization problem in Equation (6); therefore, we revert to using optimization software (e.g., MatLab) instead to get the optimal time spent on system design and outsourcing fraction given various PD scenarios. Our goal is to get managerial insights regarding the optimal strategy which maximizes the marketing window given different PD scenarios.

Performing an extensive study on various model inputs within their reasonable ranges gives a clear picture for their impact on these two decision variables (T_s and ε). To save computational time, we construct reasonable ranges for each input parameter as shown in Table 1. For instance, the information gap at which the supplier has a higher probability of failure will be around 0-0.3. Furthermore, the task size will not probably be more than 50-60% of total project time T_{total} . Therefore, λ will be within the range of (0.05-0.8).

Input parameter	Reasonable Range
Firm capability (μ)	1-6
Task size (λ)	0.05-0.8
information gap (ν)	0-0.30
Product complexity (γ)	0-0.5
Nature of detailed design work (α)	0-1.0

Table 1. Ranges for input parameters

Following these various inputs (shown in Table 1), optimal solutions for time in system design and outsourcing fraction can be obtained using MatLab. Since there are five inputs (firm capability, task size, information gap, product architecture complexity, and nature of detailed design work) with six levels each (Low1-2-3-4-5-6High), then the total optimal solutions obtained are for 5^6=15625 PD scenarios.

To see how the outsourcing fraction relates to the time spent in system design and vice versa, we solved all 5^6 data points for T_s^* and ε^*. Then, taking the average of T_s^* at various ranges for ε^* (e.g. $\varepsilon^* \in$ [0-0.1] the average T_s^* = 0.03). The result is shown in Figure 10. The figure shows an increasing relationship between the time spent in system design and the outsourcing fraction. Therefore, spending more time in system design will lead to higher amount of outsourcing or if the OEM outsource more than it is preferred to spend more time in system design.

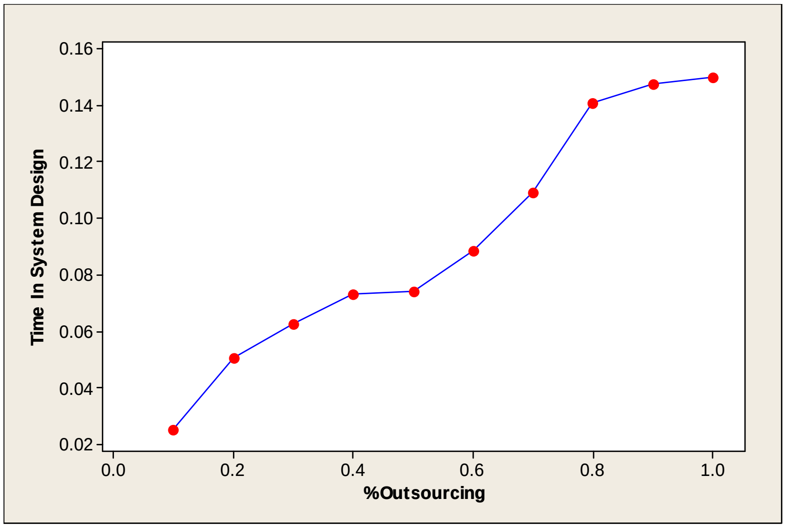

Figure 5. Time spent in system design versus outsourcing fraction

5. Sensitivity Analysis

To perform the sensitivity analyses, we combined all possible cases within the reasonable range shown in Table 1. Initially, we started with a current capability μ=1, a task size λ = 0.05, a product complexity γ=0, an information gap ν = 0, and a rework fraction α=0. Once all five input parameters are declared, then an optimal time in system design, T_s^*, and outsourcing fraction, ε^*, are computed and stored.

Then, the rework fraction, α, is incremented (by a small step size) while keeping all other four inputs at their starting values. Once the rework fraction reaches its maximum value (i.e. α=1), then a new value for the information gap (ν=0+step-size) is introduced and the rework fraction is back again to its low level (α=0). Similar update is made for product complexity, γ, when the information gap reaches its maximum value (ν = 1). Once product complexity reaches its maximum level, then a new update is made for the task size. Firm capability, μ, is incremented, when the task size reaches its maximum value of 1, until it reaches its upper limit μ_{max}. Finally, we performed extensive explorations of the stored optimal solutions in order to get the full picture behind the optimal strategy in terms of design time allocations and outsourcing for the various PD scenarios (i.e. input parameters).

5.1 Firm Capability μ

In this section we consider the average for all optimal solutions (time in system design T_s^* and ε^* optimal outsourcing fraction) at each level of firm capability μ. The result is shown in Figure 6. The figure shows that as OEM capability decreases, the amount of outsourcing increases. Obviously, to maximize the marketing window, lower OEM capability forces the OEM to spend more time in system design in order to minimize the integration failure probability. Therefore, it is better to split the work and get the benefit of the supplier's superior capability. On the other hand, having a high OEM capability makes outsourcing less attractive since the OEM can do the job relatively fast and outsourcing will only force the OEM to spend more time in system design (in order to minimize the integration failure probability). Consequently, it is optimal to spend less time in system design as firm capability increases.

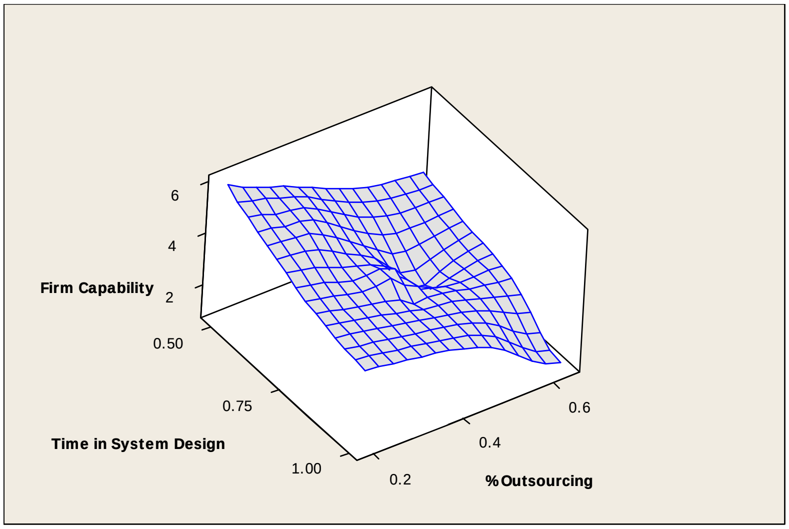

Figure 6. The effect of OEM capability on outsourcing fraction and time in system design

5.2 Task Size λ

Using similar analysis (i.e. taking the average of T_s^* and ε^* at each level of task size λ), the result is summarized in Figure 7. It can be seen that as the task size increases the OEM spends more time in system design which means that it is optimal not to gamble with large task sizes and a well defined product architecture is recommended. However, the amount of outscoring is higher at medium task sizes and lower at the edges. For large task sizes, it is optimal to outsource less (in this case <30%), because, it is risky to outsource a high fraction due to the higher chance of failure that the supplier has and the possibility of taking more time to achieve the required performance. On the other hand, when the task size is small, outsourcing forces the OEM to spend more time in system design since detailed design does not consume much time for small task sizes.

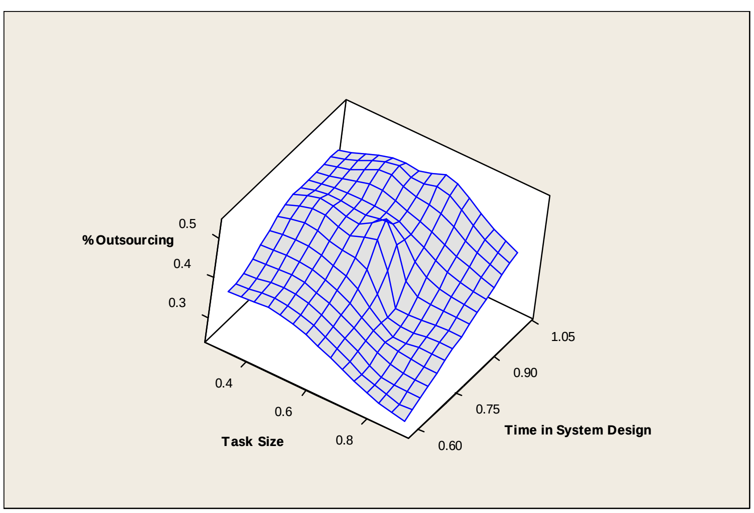

Figure 7. The effect of OEM capability on outsourcing fraction and time in system design

5.3 Product Complexity γ

Another important parameter that has an impact on the outsourcing and time allocation decisions is product architecture complexity. In Figure 8, as the complexity of the product increases, then it is essential to spend more time in system design. Moreover, the outsourcing fraction increase as the product becomes more complex. That is, for more complex products, the OEM will outsource more and spend more time in system design. It seems that splitting the task size will minimize the maximum expected time of OEM and the supplier. Therefore, achieving higher success probability for larger task sizes takes more time than having two small tasks with higher chance of integration failure.

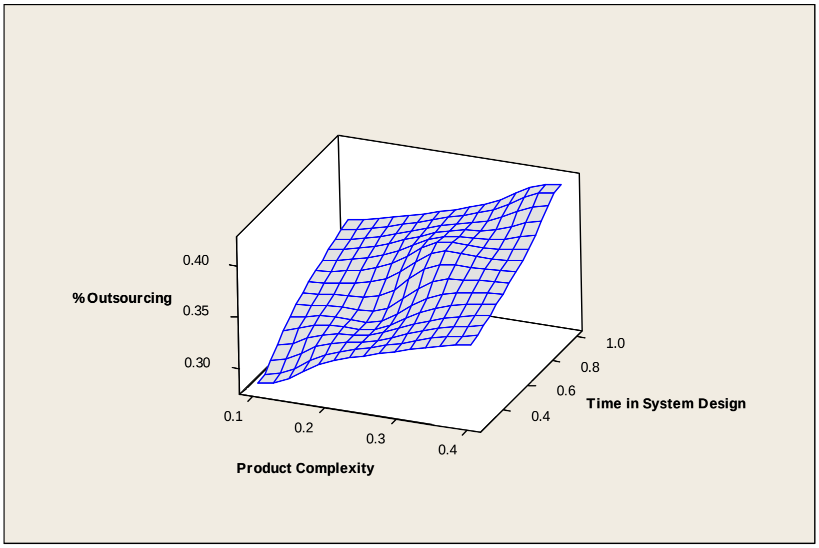

Figure 8. The effect of OEM capability on outsourcing fraction and time in system design

5.4 Fraction of Rework (detailed design nature) α

This parameter appears during the testing and integration phase as it merely dictates how much the OEM and Supplier should rework each time they fail integration and testing. Figure 9 indicates that when the fraction of rework is high, then the outsourcing fraction is low and the time spent in system design is high. However, at low rework fractions the outsourcing fraction is increased and the time in system design is shorter.

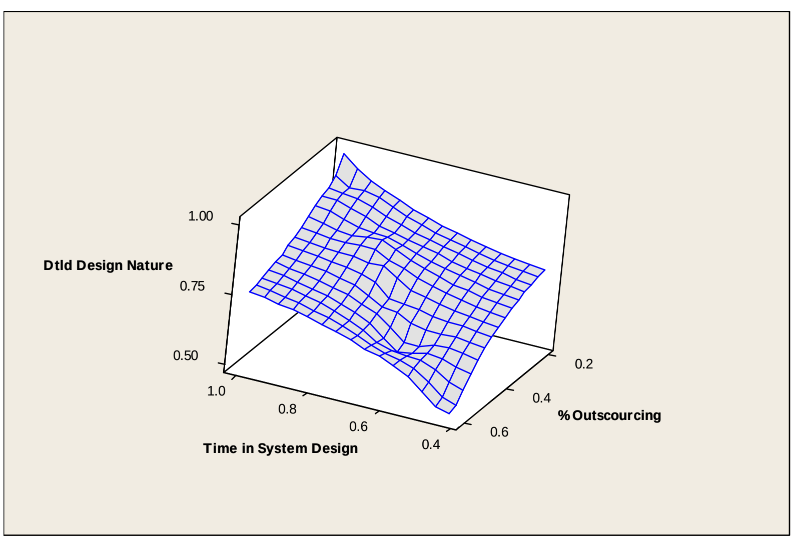

Figure 9. Effect of rework fraction on outsourcing fraction and time in system design

5.5 Supplier Total Information Gap υ

This parameter is responsible for the higher failure probability (during testing and integration) of the supplier compared to the OEM. It can be visualized as miss-communications or miss-translation between OEM and the supplier. As shown in Figure 10, as this gap increases, then it is better to spend more time in system design and outsource more. The reason is that since the OEM spends considerable time in system design, then it will end up with a well defined product architecture, where the OEM and supplier may have similar probability of success.

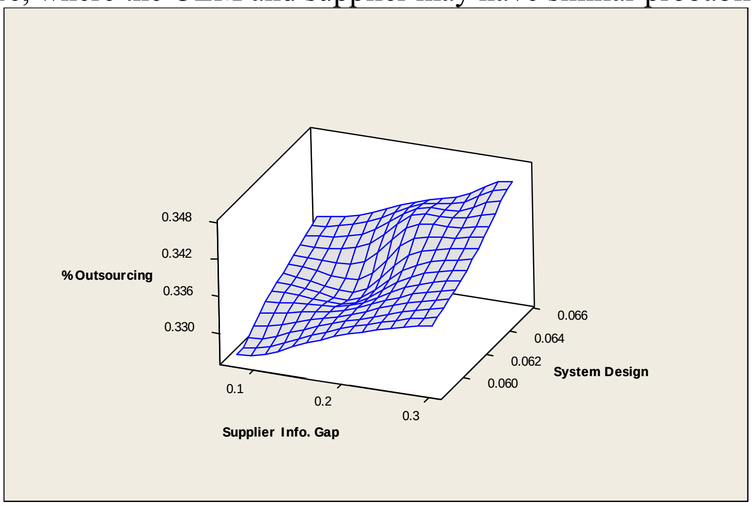

Figure 10. Effect of information gap on outsourcing fraction and time in system design

6. Summary and Conclusion

Literature suggests that outsourcing decisions are affected by product architecture and modularity, task size, firm capability, and marketing window. Therefore, in this paper, a mathematical model is developed to link all these factors and their effect on the outsourcing decision. We consider product modularity as a feature that can be obtained by spending more time in system design. This mathematical model is described as a well-bounded optimization problem where its objective is to maximize the marketing window subjected to time limitation (project total time). Different product development scenarios are examined by varying various input parameters in order to obtain the optimal strategy regarding time in system design and outsourcing fraction. A closed form solution is obtained for the binary outsourcing decision. However, for the partial outsourcing case, we use optimization software to get the optimal solution. Sensitively analyses were performed to get an overview of the impact of these inputs on the optimal solution.

The optimal solution reveals several interesting managerial insights regarding the impact of the various engineering design decisions on the outsourcing decision. First, spending more time in system design leads to higher outsourcing fraction and vice versa; that is, well defined product architectures lead to higher outsourcing. Second, higher firm capability makes outsourcing less attractive. Third, outsourcing is found to be more attractive at the medium task sizes compared to larger or smaller tasks. Fourth, a product with a complex architecture will lead the firm to spend more time in system design and thus outsource more. Lastly, the nature of the detailed design work, which determines the rework fraction, has an impact of both system time and outsourcing decisions; namely, as the rework fraction of detailed design increases, it is better to spend more time in system design and outsource more.

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