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Mathematical model to mitigate planning fallacy and to determine realistic delivery time

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Abstract Planning fallacy is the tendency to underestimate the duration of a task due to the optimistic bias of individuals. We design a mechanism from the principal's perspective (an original equipment manufacturer (OEM)) to mitigate the optimistic bias of agents (a contract manufacturer (CM) and a supplier) in a serial supply chain. The OEM determines the deadline of agents by explicitly factoring the agent's planning fallacy in the model through the cost under-estimation factor. Further, we prove that threshold based incentives are better than lump-sum bonus to motivate the supplier and the CM to mitigate procrastination of task.

Introduction

Planning fallacy is that you make a plan, which is usually a best case scenario.

Then you assume that the outcome will follow your plan, even when you should know better.

— Daniel Kahneman

The concept of time based competition, which focusses on shrinking the time required for manufacturing or business activities, is a well-researched topic in supply chain literature (Blackburn, 2012; Wadhwa, Rao, & Chan, 2005). Synonymous terms for this time based competition include fast-cycle capability, response cycle time and time compression (Bozarth & Chapman, 1996). The agreement between General Motors Corporation, an automobile company and Fisher Body Corporation, an automobile coachbuilder company (Klein, 2002; 2007), perhaps the most famous contract in the incomplete contract literature, explicitly mentions "time" in five out of ten major clauses in contracting (Guriev et al., 2005). In conjunction with the push for "time" in contracting literature, the optimistic bias in self-prediction has also amplified the planning fallacy. People anticipate that they finish their own tasks earlier than they actually do. Kahneman and Tversky (1979) define the planning fallacy as the tendency to hold a confident belief that one's own project will proceed as planned, even while knowing that a vast

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majority of similar projects have run late. Due to this optimistic prediction or underestimation of delivery time, people postpone working on the task, as they are biased towards believing that a project will be easy to complete. This planning fallacy occurs due to delusion and it may lead to procrastination of task (Ariely & Wertenbroch, 2002; Brunnermeier, Papakonstantinou, & Parker, 2008), where the actors take an inside view focussing on the specific planned action rather than on the outcomes of similar actions that have happened in the past (Flyvbjerg, Holm, & Buhl, 2002). While predicting the completion time of a task, it brings out a focus on the future rather than on the past, and people fail to make their forecasts from their past experiences.

Buehler, Griffin, and Ross (1994) also report that people underestimate their own completion time and not others' completion time. People have comparative optimism, which is a tendency to believe that they are less likely to experience negative events and more likely to experience positive events than others (Roy, Christenfeld, & Jones, 2013), (Wadhwa et al., 2005). Other terms that are used in the literature to describe this phenomenon are unrealistic optimism, optimistic bias and illusions of unique vulnerability (Buehler, Griffin, & Ross, 1995; Byram, 1997; Roy et al., 2013). The actors contribute more in exhibiting the optimistic bias towards time prediction than observers, as the actors mostly concentrate on plan based scenarios rather than on pertinent experiences in the past while making their predictions (Buehler et al., 1995; Byram, 1997; Roy et al., 2013). Besides, providing incentives for accelerated contract completion (Stalk, 1988) and choosing the lowest responsive bidder (Bajari & Ye, 2003) also enhances the underestimation and inaccuracy of time prediction. Technically speaking, imperfect forecasting techniques, inadequate data, honest mistakes, and inherent problems in predicting the future are some of the reasons for under-estimation of time (Pezzo, Pezzo, & Stone, 2006). Kaming, Olomolaiye, Holt, and Harris (1997) and Flyvbjerg (2009) stated that the main causes of time delay were related to inadequate planning, design changes, and poor labour productivity, project size, and level of competition.

The psychological explanation for over-estimation includes planning fallacy and optimistic bias (Lovallo & Kahneman, 2003), where planners and project promoters make decisions based on delusional optimism rather than on a rational weighting of gains, losses, and probabilities. The cognitive, perception and motivational processes by which people generate their predictions are an important factor affecting the degree of accuracy or bias (Kahneman & Tversky, 1979). The notion that desire for an outcome inflates the optimism about the outcome is referred to as the desirability bias or wishful thinking (Krizan & Windschitl, 2007; 2009). People can foresee the future only when it coincides with their own wishes (Orwell, 1945). The factors related to perception, such as perceived control over future events and temporal distance of future events reduce the personal risk estimate and increase the optimistic bias. The temporal planning error from over optimistic prediction leads to considerable economic implications for organisations, such as escalation of projects (Connolly & Dean, 1997). There are various endogenous, exogenous, organisational and human related factors affecting the escalation of projects that are discussed in time contingent contracts literature. Though the factors affecting the completion time is uncertain to the principal and agency, it can be estimated with the past reference data about the employees' performance.

The psychology literature has several examples for planning fallacy due to over optimism (see Armor & Taylor, 1998; Buehler & Griffin, 2003 for review). Anecdotes, archival records and surveys – all indicate that professionals and lay people are typically overly optimistic in their predictions about when projects will be completed. There are many well-known examples for underestimation including Sydney Opera House, Concorde supersonic aeroplane, Boston's Big Dig, Denver International Airport, Copenhagen metro, Northeast Corridor rail line and Channel Tunnel (Buehler et al., 1994. To the best of our knowledge, most of the studies in planning fallacy literature focus on the underestimation of time in project management problems and not on the production or manufacturing supply chain problems. This motivates us to focus on the planning fallacy in lead time/completion time estimation in a manufacturing supply chain. Though the time based competition and delivery time guarantees are an effective marketing approach, the firms should keep their promises (Shang & Liu, 2011; Stalk, 1988). Weber, Current, and Benton (1991) mention that firms pay the penalty of tardy deliveries and diminished prospects of future business, if they promise an overly-optimistic delivery date. Therefore accuracy of the lead time estimates is more important for the success of a firm. To this effect, we propose a mechanism to reduce the deviation due to optimistic prediction and determine a realistic prediction of delivery time.

The objective of this article is to develop a mathematical model involving an Original Equipment Manufacturer (OEM), a Contract Manufacturer (CM) and a supplier to avoid the mis-estimation of completion time and control the failure rate of project/task. The OEM makes equipment or components that are then marketed by its client, another manufacturer or a reseller, usually under that reseller's own name. The OEMs generally outsource the entire manufacturing of a product to the CM to reduce the labour costs, free up capital, and improve worker productivity and then concentrate on research and development, design, and marketing to enhance a product's value (Arrunada & Vázquez, 2006). There are also many OEMs who not only offload manufacturing, but also leave procurement responsibility and tasks like materials management, design and testing, order fulfilment and logistics to a speciality provider – the CM. For example, Flextronics produces cellular phones for Motorola and automotive components for Ford; Sanmina - SCI manufactures the IBM PCs in the United States (Arrunada & Vázquez, 2006). Foxconn produces Apple i-phone and i-pad, Finland's Valmet Automotive assembles the Porsche Boxster, and Austria's Magna Steyr assembles cars for Mercedes, BMW, and Saab (Ciravegna, Romano, & Pilkington, 2013). The OEM can use buy-sell or turnkey strategy for the purchase of production components (Chen, Shum, & Xiao, 2012). The scenario in which an

OEM procures components from a supplier and resells to the CM for producing final products is called buy-sell process. The setting in which the OEM delegates the control of upstream activities to the CM (component procurement) is called turnkey process. Many OEMs purchase components through the CM, for example, Dell delegates the procurement of components for its laptops and PCs to its Taiwanese contract manufacturers (CENS, 2007).

Most of the studies in outsourcing literature focus only on the game between two entities (Gray, Tomlin, & Roth, 2009 and Tan, 2001), though the outsourcing supply chain requires many entities to ease the flow of production and manufacturing process, and each entity in the chain operates subject to different sets of constraints and objectives. The performance of the entire supply chain can be improved only by optimising the objective of each of these entities which are highly interdependent (Chen et al., 2012; Guo, Song, & Wang, 2010). To bridge this gap, we consider a problem under turnkey strategy with three players in the supply chain. The OEM orders a product stating the deadline (lead time) and wage to the CM, and the CM can start the production only after receiving the production components from the supplier. The CM develops a separate contract with the supplier by estimating the lead time and wage to be given to the supplier with the wage and bonus obtained from the OEM. The OEM offers the CM a threshold based incentive for early completion of the task/product, and the manufacturer in turn offers its supplier a different threshold based incentive for exerting effort to complete early. Further, as explained by Buehler and Griffin (2003), planning fallacy also leads to procrastination, where the individuals think that the task is easy to complete and postpone working on it. Threshold based incentives help to distribute the effort during the earlier period rather than procrastinating it till the deadline, although the effort exerted by the CM and suppliers is not observable by the OEM (Wu, Ramachandran, & Krishnan, 2014). A numerical illustration to explain this phenomenon is given while introducing the mathematical model in the third section. We design a mechanism which helps to mitigate planning fallacy and procrastination of CM and supplier in a supply chain.

We contribute to the current understanding of planning fallacy by: (1) designing a mechanism where the deadline for the CM and the supplier can be estimated by the OEM by anticipating their actual completion times; (2) explicitly factoring the actor's planning fallacy in the model through the cost under-estimation factor; (3) analytically showing that under threshold-based mechanism, the completion time of the player in the supply chain will be less than the imposed deadline, even without any external penalty mechanism; (4) mathematically proving that under lump sum-bonus-based incentive, the completion time of the supplier and the CM will be equal to or higher than the imposed deadlines.

Observations from literature

This work is evolved from multiple streams of literature including the lead time estimation in supply chain and planning fallacy due to optimistic prediction of completion time.

Lead time estimation in supply chain

Lead time is defined as the time between starting the processing of the order and the order's arrival time (Keskinocak, Ravi, & Tayur, 2001). Leng and Parlar (2009) classified the lead time into three components – set up time, production time and shipping time. Most of the lead time estimates are available in scheduling the jobs, for example, Yano (1987) determined the optimal planned lead times in serial production systems when the procurement and processing times are stochastic. Song (1994) studied the impact of stochastic lead time on optimal inventory decisions. Palaka, Erlebacher, and Kropp (1998) studied the impact of quoted lead time and pricing on demands. Easton and Moodie (1999) estimated the lead time based on the available capacity and backlog. Keskinocak et al. (2001) analysed the problem of scheduling and lead-time quotation when revenues decrease with lead times and the orders have an availability interval. Lederer and Li (1997) and So (2000) analysed the interaction between price and delivery time performances in a competitive market. Ray, Gerchak, and Jewkes (2004) developed a model to estimate optimal inventory policy and lead time that would minimise firm's inventory cost in make-to-stock environment. Shang and Liu (2011) have analysed the estimation of lead time and benefits of faster delivery time guarantees for make-to-order products under competitive conditions. The existing literature discusses only the lead time estimates given by the CM or supplier (agency) who actually processes the product or task. The CMs or suppliers have a tendency to quote an optimistically biased lead time to show its performance in the competitive market and to win the bid. We consider the lead time estimation from the principal's point of view.

Optimistic bias and the factors affecting it

The optimism bias (also known as unrealistic or comparative optimism) is a bias that causes a person to believe that he is less at the risk of experiencing a negative event than his peers (Weinstein, 1980). The optimistic bias exists for both men and women, and across age and educational levels (Weinstein, 1980). The temporal planning errors from over optimistic prediction lead to considerable economic implications for organisations (Connolly & Dean, 1997) and cause job losses due to escalation (Beuhler & Griffin, 2003). Agency escalates the projects for self-justification of their prediction in the planning phase and this is seen as irrational for the principal and the organisation. Further, unrealistic targets and prolonged completion times can result in employee stress, frustration, disappointment, and reduced job satisfaction during task completion (Boltz & Yum, 2010). While much evidence from the literature suggests that the optimistic beliefs are optimal (Armor & Taylor, 1998), this may have detrimental consequences as well. Kahneman and Tversky (1982) define the "planning fallacy" as the behaviour by which people tend, both, to underestimate the time necessary to complete an unpleasant task, and postpone working on the task as they are biased towards believing that the project will be easy to complete.

The cognitive, perception and motivational processes by which people generate their predictions are an important factor affecting the degree of accuracy or bias (Kahneman & Tversky, 1979 and Griffin, Dunning, & Ross, 1990). Weinstein (1980) suggests a positive relationship between optimistic bias and perceived control. When people perceive greater control over future events, their personal risk estimates will reduce and their optimistic bias will increase. Forward-looking agents care about expected utility flows, and enjoy anticipatory utility if they are optimistic about the future (Caplin & Leahy, 2001). Circumstances that prompt the individuals to predict earlier completion times such as monetary incentives (Buehler et al., 1995; Buehler, Griffin, & MacDonald, 1997; Klein & Helweg-Larsen, 2002) or the desire to please others also increase the degree of optimistic bias in prediction. Temporal proximity of a project is an important determinant of how people generate their predictions. In the process of planning and prediction, temporal closeness of future events enhances people's thoughts about specific obstacles they might encounter (e.g., task difficulties, competing time demands, etc.) resulting in less optimism for imminent events than distant performances (Roy & Christenfeld, 2008). Future tastes and beliefs of a person may differ from current tastes depending on factors such as habit formation, day-to-day mood fluctuations, age, social influences, inter temporal distance of deadlines, locus of control, perceived control, and changes in the environment (Klein & Helweg-Larsen, 2002; Loewenstein, O'Donoghue, & Rabin, 2000). People overestimate their past achievements, abilities, and other desirable traits relative to others, which would contribute to optimistic bias (Pinto, 2013).

Research gap

An ample amount of research has been done to find ways that can focus on time based objectives to enhance the efficiency of supply chain (Chen et al., 2012; De Treville, Shapiro, & Hameri, 2004). However, the cognitive bias of individuals which affects the prediction of time has not been studied in supply chain literature. Although the planning fallacy of individuals is well documented in project management literature, to the best of our knowledge, the influence of optimistic thinking on lead time prediction in the context of outsourcing has not been examined. Further, most of the problems in time contingent contracts or outsourcing literature consider the supply chain issues between two players (Tan, 2001) and do not adequately focus on problems involving multiple players. However, the outsourcing supply chain requires multiple players to smoothen the flow of production and operation (Guo et al., 2010). To bridge this gap, we discuss the problem of planning fallacy in the outsourcing supply chain containing three players, viz the supplier, the CM and the OEM to determine the realistic estimate of completion time. The delivery time is generally estimated by the supplier or contract manufacturer who is adding value to the product (the supplier or the CM) with the past information available (Duenyas & Hopp, 1995; Öztürk, Kayalıgil, & Özdemirel, 2006). However, most of the estimates predicted by the supplier or the CM are unrealistic or overly optimistic leading to planning fallacy. To mitigate this problem, Roy et al. (2013) proposed that the observer can predict the completion time to eliminate the prediction bias of the actors. We use this strategy in our model and determine the delivery time from the OEM's perspective such that it helps in minimising the mis-estimation of delivery time due to over-optimism and also prevents escalation. Further, in scheduling literature the due date is proposed, with a penalty for earliness and tardiness (Dileepan, 1993). However, we offer threshold based incentives for early completion and penalty for tardy completion.

Problem description

In lump sum incentive scheme, a fixed bonus is offered irrespective of the amount of time saved from the deadline. It is optimal for the agent to complete the task on the deadline, since she can get the incentive regardless of the time saved. The proof to show that the completion time is the same as the optimal deadline in case of lump sum incentive model is given in Note 1 in Appendix I. In the threshold incentive scheme, a variable bonus is offered based on the amount of time saved from the deadline announced. The threshold incentive and lump sum incentive schemes are commonly used in the marketing literature Caliskan Demirag, (2011); Sohoni, Bassamboo, Chopra, Mohan, and Sendil (2010); (2011). The supply chain is said to perform better with an additional marginal payment in the threshold incentive scheme (Caliskan Demirag, 2011). The objective of decreasing the actual completion time, so that the task is completed much before the deadline offered to the agent is similar to increasing the demand beyond sales threshold (which is commonly studied in the marketing literature). Hence, we investigate if the threshold-based incentive scheme can be adopted to minimise the planning fallacy in the supply chain. The agents (the supplier and the CM) prefer lump sum bonus, since the bonus obtained in case of the lump sum scheme by completing on the deadline is higher than the threshold based scheme. However from the principal's perspective, it is optimal to offer threshold based incentive to complete early, since the agent exerts effort from the beginning to complete the task before the deadline. Further this helps mitigate the procrastination by distributing the effort evenly, since the reduction in each unit of time brings an additional bonus to the agent. The mathematical proof for the completion time to be less than the deadline offered is given in Note 2 and Note 3 in Appendix II.

We formulate a mathematical model to determine the delivery time and study the impact of threshold based incentives in a three player supply chain. The problem is solved at two levels using backward induction. A schematic representation of the contract flow in the supply chain is given in Fig. 1.

First, the OEM offers a contract to the CM to produce a product, and the CM in turn produces it after delivery of the raw material from the supplier. In this set up, the OEM will have a contract with the CM to deliver the task in a given deadline and there is no contract between the OEM and

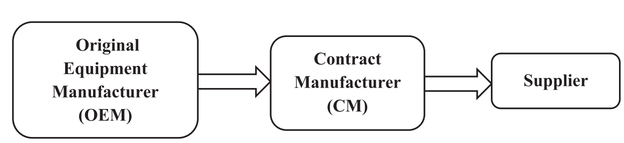

Figure 1 A schematic representation of the contract flow for the problem.

supplier. The CM will contract with the supplier for material or parts delivery and starts the production after the supplier delivers. Hence the compensation scheme for the supplier will be determined by the CM from the wage he receives from the OEM for producing the product. We develop a mathematical model from the OEM's perspective to quote a delivery time to the CM by anticipating the delivery time quoted by the CM to the supplier. While predicting the delivery time, we assume that the cost information of the supplier is common knowledge to the CM and the OEM. This is a commonly-used assumption in game theory models (Monderer & Samet, 1989) and also in multi-tier supply chain models (Tsay, 1999). The parameters such as time sensitivity factor for the supplier (a), cost per unit of time reduced by the supplier (c), market wage and bonus obtained by the supplier (w_s and b_s) are known to the OEM from the history of past contracts with the supplier or from the market.

In this three player contract, OEM (principal) offers the CM (intermediate agency) a threshold based incentive for early completion of the product, and the CM in turn offers the supplier (agent) a different threshold based incentive for exerting effort to deliver the raw material early. Supplier and CM pay the penalty to their downstream members for tardy delivery proportional to the amount of tardiness (Cai, Zhou, & S., 1997). We assume that the wage is dependent on the actual completion time and time sensitive factor associated with it. The time sensitive factor is the x- intercept value of inverse time function, where the inverse time function maps the amount of completion time taken to the market wage for that time. The function consists of highest market wage that can be given for the time taken, time sensitive factor, which implies the sensitivity of the market wage towards the actual time taken. The wage per unit of time reduces for the higher value of time sensitive factor. This function is similar to the price dependent demand function used in newsboy problem (Anderson, 1980; Lau & Lau, 1988). As the exertion of the supplier's effort cannot be observed by the CM and the CM's effort cannot be observed by the OEM, the incentive is offered to motivate early completion. We find the optimal wage to be offered from the actual completion time. First, the OEM offers the CM a deadline and corresponding wage to deliver the product, and then the CM contracts for a delivery deadline and wage per day to the supplier accordingly. We solve the problem from the OEM's perspective to find the realistic delivery deadline to be given to the CM anticipating the wage and bonus to be offered by the CM to the supplier. Though the OEM cannot control the wage to be offered to the supplier, we solve for the case where the information about the time sensitive factors of CM and supplier are common knowledge to the OEM from the past records. A schematic representation of the sequence of actions is given below in Fig. 2.

Mathematical model to find the optimal deadline to be offered and the actual completion time

The sequence of action follows (i) first the OEM announces the delivery deadline, wage and bonus to the CM satisfying the individual rationality and incentive compatibility of the CM (ii) CM accepts to participate in the contract and then announces a wage, bonus and deadline for the supplier which satisfies the individual rationality and incentive compatibility of the supplier (iii) lastly, the supplier accepts to participate in the contract and finds the actual completion time based on the wage, bonus and deadline offered.

A normal form game with a risk neutral OEM is a tuple $Z = (N, \Omega, \pi)$ where,

- N = 3, i.e. the OEM, CM and supplier
- $\Omega = \{d_s, T_s, d_m, T_m\}$, i.e. deadline and actual completion time for supplier and contract manufacturer
- $\pi = \{\pi_S, \pi_M, \pi_R\}$, i.e. profit of supplier π_S, profit of contract manufacturer π_M and profit of OEM π_R

Mathematical model for lump sum incentives

Profit of supplier

The profit function of supplier (π_S) contains wage, bonus and cost function. We assume a time dependent wage function for every time unit (inverse wage function), where the function maps the market wage to the completion time (dependent variable) (Lee, 1978). The function consists of a market wage (w_s), time sensitive factor (a) and the actual completion time (T_s) to determine the optimal wage. The bonus function in the lump sum model contains a fixed bonus (b_s) to be offered when the task is completed on or before deadline (Sodhi & Tang, 2013), where the same bonus is offered irrespective of the amount of time saved from deadline. The cost function contains the corresponding cost (cT_s) to reduce the time. In addition to the cost in the lump sum scheme, there is a penalty imposed in the quadratic form to penalise the deviation of completion time from the deadline.

$$\pi_S = (w_s - aT_s)T_s + b_s - cT_s - k_s(d_s - T_s)^2 \qquad \text{(i)}$$

Profit of contract manufacturer

The profit function of CM (π_M) contains a wage dependent time function, where the wage per unit time taken by the CM and the supplier is given to the CM by the OEM. Similar to the wage dependent time function of the supplier, the optimal wage for the CM depends on the market wage (w_m), time sensitive factor (x) and the actual completion time of CM (T_m). Similar to the lump sum incentive scheme for the

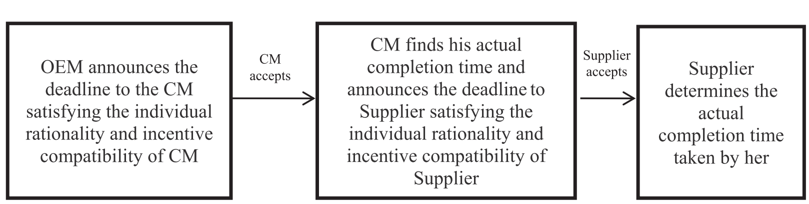

Figure 2 Sequence of actions for first configuration.

supplier, the CM is also offered a lump sum bonus and a penalty for deviating from the deadline. The cost function contains the wage and bonus to be given to the supplier in addition to the cost incurred for completion time.

$$\pi_M = (w_m - x(T_s + T_m))(T_s + T_m) + b_m - y(T_s + T_m) - k_m(T_m - (d_m - T_s))^2 - (w_s - aT_s)T_s - b_s \quad \text{(ii)}$$

Profit of original equipment manufacturer

The profit function of OEM (π_O) contains a selling price from the customer / market in the form of wage dependent time function. This function depends on the market price of the product (V), time sensitive factor for OEM wage (p) and the actual completion time of CM and supplier (T_m and T_s). Then, a lump sum bonus is earned from the market for early availability of product. The cost function contains the respective cost for total time taken plus the wage and bonus to be given to the CM. Similar to supplier and CM, OEM will also incur a penalty for exceeding the deadline.

$$\pi_O = (V - p(T_m + T_s))(T_m + T_s) + R - k_o(T_m - (d_m - T_s))^2 - (w_m - x(T_s + T_m))(T_s + T_m) - b_m \quad \text{(iii)}$$

Solution methodology

The decision variables in this contract are the actual completion time taken by the supplier and the CM, and the deadline to be given to the supplier and the CM. The optimisation problem is solved using backward induction at two levels. The OEM first solves the supplier's profit function to find the actual completion time (T_s) of the supplier firm considering the deadline given to the supplier. The wage and bonus to be given to the suppliers can be found from the actual completion time of the supplier (through the wage dependent time function). The OEM then solves the CM's profit function to find the actual completion time of CM (T_m) and optimal deadline to be announced to the supplier (d_s) considering the deadline announced by the OEM to the CM. The wage dependent time function for the CM helps to find the actual wage and bonus to be given to the CM. Lastly, the profit of the OEM is maximised to find the optimal deadline to be announced to the CM (d_m) from the anticipated delivery deadline, actual completion time and wage for the suppliers and the CM. The proof of the results is given in Appendix I.

Theorem 1. The extensive form game $Z = (N, \Omega, \pi)$ has unique subgame perfect Nash equilibrium T_s^*, d_s^*, T_m^* *and* d_m^*

Proof. The solution of the game $Z = (N, \Omega, \pi)$ can be found using backward induction. The supplier's completion time (T_s^*) for a given deadline from CM is unique from Lemma 4. Similarly, the CM's completion time (T_m^*) and the deadline to be offered to supplier (d_s^*) for a given deadline from CM is also unique from Lemma 5. Also, anticipating the unique best response from the supplier and the CM, the OEM maximises his profit. From Lemma 6, it is clear that the OEM's optimal decision is also unique.

Results for lump sum incentive

The supplier's optimal completion time is given by,

$$T_s{}^* = \frac{-c + 2d_s k_s + w_s}{2(a + k_s)} \quad \text{(iv)}$$

The CM's optimal completion time is given by,

$$T_m^* = -\frac{ay - 2ad_m k_m - aw_m + xw_s + k_m w_s}{2a(x + k_m)} \quad \text{(v)}$$

The supplier's deadline is given by,

$$d_s^* = \frac{1}{2}\left(\frac{c}{k_s} + \frac{w_s}{a}\right) \quad \text{(vi)}$$

The CM's deadline is given by,

$$d_m^* = \frac{Vx + py - xy + k_m(V - w_m) - pw_m}{2(p - x)k_m} \quad \text{(vii)}$$

Mathematical model for threshold based incentives

The only “threshold” in the threshold based incentives scheme is the deadline given to the supplier and the CM, imposed by the CM and the OEM, respectively (d_s and d_m). The threshold (deadline) offered for an agent will not vary over time (only single threshold is analysed). The lump sum incentive offered is akin to a fixed incentive scheme; whereas the threshold incentive works like the variable incentive. Hence, for a given threshold (same in both the schemes), the bonus obtained by the agent in threshold based incentive scheme will vary based on the actual completion time. However, the bonus does not vary in the lump sum incentive scheme.

Let us consider a numerical illustration to explain that the threshold based incentives are better from the principal's perspective (one who offers the incentive) and lump sum incentives are better from the agent's perspective (the one who gets the incentive from the principal). Let us assume that the lump sum bonus announced by the upstream player (the CM) to the subsequent downstream player (the supplier) is Rs100 for completing the task on or before the deadline (say 10 days from signing the contract). In this scheme, it is optimal for the agent to finish on the 10th day to get the incentive of Rs 100. However in case of the threshold based incentive scheme, for the same threshold deadline (i.e. 10 days after signing the contract), if the bonus (b_s) per unit of time saved is Rs100, the agent should finish on the 9th day to get the same incentive of Rs 100. In this type of incentive scheme, the agent will exert the effort from the beginning of the task (day one) to increase the incentive obtained, which helps in mitigating the procrastination of the task. The upper limit for the magnitude of bonus in case of the threshold based scheme can be decided from the opportunity cost of the principal per unit time saved. However, the lower limit cannot be less than the lump sum bonus to satisfy the individual rationality of the agent in the threshold based scheme. If the revenue obtained by the principal elsewhere is less than the lump sum bonus, then the principal cannot benefit by offering the threshold based incentive scheme. However in an outsourcing supply chain where a CM can find plenty of opportunities from multiple OEMs, the profit obtained by the principal by saving a unit of time is very high. Further, the OEM is also interested in offering threshold based incentive scheme as he can increase his profit by releasing the product on time to the market. The lump sum incentive based scheme is preferred only in a scenario when the manufacturer does not want to carry the supplier inventory in the warehouse till the production starts. Hence, when the early delivery of product to the upstream member is beneficial to the principal, it is always optimal for the principal to offer threshold based incentive than the lump sum incentive.

Profit of supplier

Similar to the wage function used in lump sum model, the time dependent wage function is used in the threshold based incentive model as well. The bonus function in this model contains the bonus for the units of time saved from the deadline announced $b_s(d_s - T_s)$, where the deadline is the threshold given. The cost function in this model is the effort incurred to reduce the completion time from the deadline announced $c(d_s - T_s)^2$, where c is the actual cost coefficient per time unit and it is the actual completion. The threshold based incentive in itself will ensure that the $d_s \geq T_s$ without using any external penalty mechanism. The condition under which $d_s \geq T_s$ is given before the results section. The profit function of the supplier without any optimistic bias is given in Eq. (1). However, if the supplier exhibits over optimistic behavior, it leads to planning fallacy.

We quantify the optimistic bias of the supplier using a factor called cost salience (e), which is the cost perceived by the supplier to complete the task. The cost perceived by the supplier is less than the actual cost incurred, due to underestimation of actual cost (e). We use a quadratic form similar to (Weber et al., 1991) to model the cost of effort required. We assume that the market wage and bonus to the supplier and CM firm, and their time sensitive factor, cost factor and cost salience factor are common knowledge to the OEM. The impact of this time sensitive factor for supplier wage (a), cost coefficient (c), cost salience (e) and the penalty of supplier (p_s) on the deadline, and completion time of CM and supplier are shown in section 4. The supplier optimises the completion time required with the deadline announced by the CM. There is a difference in the optimal completion time estimated when the cost of the supplier is underestimated ($e < 1$) and not underestimated ($e = 1$) in the model. The difference between deadline and completion time is the actual cutback (reduction) in time that can be achieved by offering threshold based incentives. However due to over optimism, the supplier perceives that the cost incurred for this cutback in time is less than the actual cost. When the supplier underestimates the actual cost, this cutback in time will become an unrealistic estimate. This difference is purely a realisation of the planning fallacy. Similarly, the supplier can also overestimate the value of bonus she receives, which would also lead to planning fallacy. The optimal completion time in this case is determined by including an overestimation factor greater than one in the bonus function. To mitigate the planning fallacy, the OEM designs a penalty mechanism, where a penalty is included as a function of the underestimated cost value for each unit of time reduced. To make the intensity of penalty equivalent to the underestimation in cost function, the penalty function is also made quadratic. The modified profit function with penalty mechanism to mitigate planning fallacy is given in *I*.

The profit function of supplier without optimistic bias is:

$$\pi_S = (w_s - aT_s)T_s + b_s(d_s - T_s) - c(d_s - T_s)^2 \tag{1}$$

The profit function of supplier to mitigate planning fallacy is:

$$\pi_S = (w_s - aT_s)T_s + b_s(d_s - T_s) - ec(d_s - T_s)^2 - (1-e)p_s(d_s - T_s)^2 \tag{I}$$

Profit of contract manufacturer

The profit function of CM (π_M) contains a wage dependent time function similar to the supplier wage function used in the lump sum model. Likewise, a bonus is offered for the amount of time saved by CM and supplier together from the deadline given for CM ($d_m - T_m - T_s$) (threshold based incentive, (Sodhi & Tang, 2013). This bonus is offered by OEM, since he can certainly generate substantial early-bird revenue, if the product is released early in the market. Hence, the bonus is quantified in terms of the amount of time saved from the actual lead time (deadline) announced. There is also a cost of effort incurred to indicate the effort required to reduce the completion time from the deadline, where y is the cost coefficient. The profit function of CM without optimistic bias is given in (2). Similar to the cost salience factor used for supplier, the CM also underestimates the actual cost (y) to a lesser value (fy), where the cost salience factor (f) takes the value less than one while under estimating the cost. Otherwise, the cost to the CM includes the wage and bonus to be offered to the supplier. The order of time sensitive factor x and cost coefficient y will alter their impact on the deadline and completion time of CM. The modified profit function (given in *II*) with penalty mechanism to mitigate planning fallacy includes a penalty cost of $(1-f)$ $p_m(d_m - T_m - T_s)^2$ in addition to the underestimated cost. The penalty for CM (p_m) will be higher than the cost coefficient of CM (y) to ensure that the penalisation for underestimation of cost will avoid over optimism. Further this penalty is imposed on the CM by the OEM will be higher than penalty obtained by OEM from the market (p_o) for planning fallacy. The same logic applies while the CM penalises the supplier, hence the penalty given to supplier by CM (p_s) will be less than the penalty obtained by the CM from the OEM. The cost salience factor will be equal to one when the CM does not underestimate the cost. In such a case no penalty is imposed. The CM optimises the profit function to determine the completion time required (T_m) and the deadline to be announced to the suppliers (d_s) from the deadline given to CM (d_m). The completion time for the CM is higher than the deadline or completion time for the supplier, since the CM starts the production only after receiving material from the supplier. Further, the deadline given for supplier (d_s) will be less than the deadline of CM (d_m).

The profit function of CM without optimistic bias is:

$$\pi_M = \left(w_m - x(T_s + T_m)\right)(T_s + T_m) + b_m(d_m - T_s - T_m) - y(d_m - T_m - T_s)^2 - (w_s - aT_s)T_s - b_s(d_s - T_s) \tag{2}$$

The profit function of CM to mitigate planning fallacy is:

$$\begin{aligned}\pi_M = & \left(w_m - x(T_s + T_m)\right)(T_s + T_m) + b_m(d_m - T_s - T_m) \\ & - fy(d_m - T_m - T_s)^2 - (1-f)p_m(d_m - T_m - T_s)^2 \\ & - (w_s - aT_s)T_s - b_s(d_s - T_s)\end{aligned} \tag{II}$$

Profit of original equipment manufacturer

The profit function of OEM (π_O) contains a wage dependent time function from market, same as the lump sum model. Further, similar to the bonus function of other players, the OEM gets a threshold from the customer for early availability of product in the market. The OEM is offered a bonus (R) from the market for early availability of product in the market. The cost incurred by the OEM under threshold scheme is the wage and bonus given to CM in addition to the effort exerted $q(d_m - T_m - T_s)^2$ for saving time, where q is the cost coefficient of OEM. The OEM optimises the optimal deadline to be announced to the CM (d_m). The deadline given to CM is estimated by anticipating both the completion time taken by CM and supplier. The order of deadline and completion time of CM and supplier follows $d_m > T_m > d_s > T_s$. The profit function without optimistic bias is given in (3). The profit function of OEM to mitigate planning fallacy is the same as the profit function without optimistic bias. Since the model is solved from the perspective of the OEM, the OEM does not have any optimistic bias. However, the results from these two cases are different, since the result for CM (d_s and T_m) and supplier (T_s) varies.

The profit function of OEM without optimistic bias is:

$$\begin{aligned}\pi_O = & \left(V - p(T_m + T_s)\right)(T_m + T_s) + R(d_m - T_m - T_s) \\ & - q(d_m - T_m - T_s)^2 - \left(w_m - x(T_s + T_m)\right)(T_s + T_m) \\ & - b_m(d_m - T_m - T_s)\end{aligned} \tag{3}$$

The profit function of OEM to mitigate planning fallacy is:

$$\begin{aligned}\pi_O = & \left(V - p(T_m + T_s)\right)(T_m + T_s) + R(d_m - T_m - T_s) \\ & - q(d_m - T_m - T_s)^2 - \left(w_m - x(T_s + T_m)\right) \\ & (T_s + T_m) - b_m(d_m - T_m - T_s)\end{aligned} \tag{III}$$

The solution methodology in the threshold based incentive model is the same as the procedure explained in the lump sum model. The proof of the results for threshold based incentive model is given in Appendix II.

Uniqueness of Nash equilibrium for threshold based incentive without optimistic bias

Lemma 4. *The supplier's profit function π_S is strictly concave w.r.t. T_s*

Lemma 5. *The CM's profit function π_M is strictly concave w.r.t. d_s and T_m*

Lemma 6. *The OEM's profit function π_O is strictly concave w.r.t. d_m*

Theorem 2. The extensive form game $Z = (N, \Omega, \pi)$ has unique subgame perfect Nash equilibrium T_s^*, d_s^*, T_m^* and d_m^*
Proof. The solution of the game $Z = (N, \Omega, \pi)$ can be found using backward induction. The supplier's completion time (T_s^*) for a given deadline from CM is unique from Lemma 1. Similarly, the CM's completion time (T_m^*) and the deadline to be offered to supplier (d_s^*) for a given deadline from CM is also unique from Lemma 2. Also, anticipating the unique best response from supplier and CM, the OEM maximises his profit. From Lemma 3, it is clear that the OEM's optimal decision is also unique.

Lemma 7. The supplier's profit function π_S is strictly concave w.r.t. T_s

Lemma 8. The CM's profit function π_M is strictly concave w.r.t. d_s *and* T_m

Lemma 9. The OEM's profit function π_O is strictly concave w.r.t. d_m

Theorem 3. *The extensive form game $Z = (N, \Omega, \pi)$ has unique Subgame Perfect Nash Equilibrium T_s^*, d_s^*, T_m^* and d_m^**
Proof. The solution of the game $Z = (N, \Omega, \pi)$ can be found using backward induction. The supplier's completion time (T_s^*) for a given deadline from the CM is unique from Lemma 1. Similarly, the CM's completion time (T_m^*) and the deadline to be offered to supplier (d_s^*) for a given deadline from the CM is also unique from Lemma 2. Also, anticipating the unique best response from supplier and CM, the OEM maximises his profit. From Lemma 3, it is clear that the OEM's optimal decision is also unique.

Results for threshold based incentive

The optimal wage and bonus for all the players in all three configurations are dependent on time (inverse time function). (Table 1)

Threshold based incentive (TBI) without underestimation of cost (*e*, *f* = 1) and with underestimation of cost (*e*, *f* < 1)

The supplier's optimal completion time is given by,

$$T_s^* = \frac{-b_s + 2cd_s + w_s}{2(a+c)} \text{ and } T_s^* = \frac{-b_s + 2ced_s + w_s}{2(a+ce)} \tag{4}$$

The CM's optimal completion time is given by,

$$\begin{aligned}T_m^* &= -\frac{acb_m + a(x+y)b_s + c(-2ayd_m - aw_m + xw_s + yw_s)}{2ac(x+y)} \text{ and} \\ T_m^* &= -\frac{aceb_m + a(x+fy)b_s + ce\left(-2afyd_m - aw_m + (x+fy)w_s\right)}{2ace(x+fy)}\end{aligned} \tag{5}$$

The supplier's deadline is given by,

$$\begin{aligned}d_s^* &= \frac{a(a+2c)b_s + c^2 w_s}{2ac^2} \text{ and} \\ d_s^* &= \frac{a(a+2ce)b_s + c^2e^2 w_s}{2ac^2e^2}\end{aligned} \tag{6}$$

Table 1 Time dependent wage and bonus.

Supplier's wage (W_s)	$(w_s - aT_s)T_s$
Supplier's bonus (B_s)	$b_s(d_s - T_s)$
CM's wage (W_m)	$\left(w_m - x(T_s + T_m)\right)(T_s + T_m)$
CM's bonus (B_m)	$\left(b_m(d_m - T_s - T_m)\right)$
OEM's wage (W_r)	$(V - p)(T_s + T_m)(T_s + T_m)$
OEM's bonus (B_r)	$R(d_m - T_s - T_m)$

The CM's deadline is given by,

$$d_m{}^* = \frac{-ac(x^2-py+xy)b_m + a\left(qx^2+(p-x)y^2\right)b_s - c(ax(Rx+Vy)-apyw_m\left(qx^2+(p-x)y^2\right)w_s}{2ac\left(qx^2+(p-x)y^2\right)}$$

and (7)

$$d_m{}^* = \frac{(x+fy)(Rx+fVy)-(qx+x^2-fpy+2fxy)b_m+\left(qx-fy(p+fy)\right)w_m}{2\left(qx^2+f^2(p-x)y^2\right)}$$

Threshold based incentive to mitigate planning fallacy

This model contains the penalty mechanism for optimistic bias of a player, which helps to reduce the underestimation of cost and mitigate planning fallacy.

The supplier's optimal completion time is given by,

$$T_s{}^* = \frac{-b_s+2d_s(ce+p_s-ep_s)+w_s}{2\left(a+ce-(-1+e)p_s\right)} \tag{IV}$$

The CM's optimal completion time is given by,

$$T_m{}^* = -\frac{\begin{array}{c} ab_s\left(x+fy-(-1+f)p_m\right)+ab_m\left(ce-(-1+e)p_s\right) \\ -\left(ce-(-1+e)p_s\right)\left(2ad_m\left(fy-(-1+f)p_m\right)\right. \\ \left.+aw_m-(x+fy+p_m-fp_m)w_s\right) \end{array}}{2a\left(x+fy-(-1+f)p_m\right)\left(ce-(-1+e)p_s\right)} \tag{V}$$

The supplier's deadline is given by,

$$d_s{}^* = \frac{ab_s\left(a+2ce-2(-1+e)p_s\right)+\left(ce-(-1+e)p_s\right)^2w_s}{2a\left(ce-(-1+e)p_s\right)^2} \tag{VI}$$

The CM's deadline is given by,

$$d_m{}^* = \frac{\begin{array}{c} Rx^2+fRxy+fVxy+f^2Vy^2-b_m(qx+x^2-fpy+2fxy+ \\ (-1+f)(p-2x)p_m)+qxw_m+(-1+f)^2p_m{}^2(V-w_m)-fpyw_m \\ -f^2y^2w_m-(-1+f)p_m\left(Rx+Vx+2fVy-(p+2fy)w_m\right) \end{array}}{2\left(qx^2+f^2(p-x)y^2-2(-1+f)f(p-x)yp_m+(-1+f)^2(p-x)p_m{}^2\right)} \tag{VII}$$

Analysis of results

We assume that the factor representing time sensitivity of an upstream player will always be higher than the downstream player and the same order applies for cost coefficient factor of players as well. This assumption is practical in the sense that their distance from the end-user is higher. Irrespective of the order of these factors, the design for the threshold based incentive (TBI) model shows that the deadline of any player is always higher than the completion time of that player. We plot the difference between deadline and completion time of supplier $(d_s - T_s)$ and deadline and completion time of CM $\left(d_m-(T_s+T_m)\right)$ as a function of all parameters of the model. In other words, the cutback in time of the supplier and the cutback in time of the CM are plotted as a function of all the parameters. The graphs are plotted for three different cases of the TBI model and the lump sum model which includes, (1) TBI model without underestimated cost (dotted line), (2) TBI model with underestimated cost (solid black line), (3) TBI model to avoid planning fallacy (which includes the penalty for underestimation of cost, dashed line) and (4) lump sum model (dotted and dashed line parallel to x-axis).

Fig. 3a shows the plot for difference between deadline and completion time for supplier (d_s - T_s) as a function of supplier's cost (c) for four different variations in the model. Similarly, Fig. 3b shows the difference between deadline and completion time for CM (d_m -T_m) as a function of cost coefficient for the CM (y). The plot for TBI without underestimated cost shows the actual cutback in time, and the plot for TBI with underestimated cost shows that the cutback in time is overestimated. We also analytically prove that the difference between deadline and completion time is overestimated when the supplier or the CM underestimates the actual cost by being over-optimistic. Fig. 3a shows this result for supplier as a function of c. Further it is apparent that the reduction of time from deadline is highly over estimated, when the cost incurred by the supplier is very little. However for CM (see Fig. 3b), the cutback in time for underestimation of cost model is dominated only after a certain value of y. We refer to this value of cost as y^* (see the intersection point in Fig. 3b). Hence even when the CM underestimates the cost, the underestimated cost incurred to CM (y) should be less than fy^* to reduce planning fallacy. Hence to avoid the planning fallacy irrespective of the value of cost salience of supplier and CM (e, f), a penalty mechanism for underestimation of cost is included in the threshold based incentive model. This model is not influenced by the cost coefficient of the supplier (c) (see Fig. 3a), whereas the increase in cost factor of the CM reduces the cutback in time for this model (see dashed line in Fig. 3b). It is also seen that there is no difference between the deadline and completion time of the supplier or the CM when lump sum incentive is offered, irrespective of the cost incurred by the supplier and the CM.

In contrast to the cost factor of the CM, the increase in time sensitive factor for the CM (x) increases the cutback in time ($d_m - T_m - T_s$) (See Fig. 4a). If the time sensitivity of the CM (x) is less than the cost factor (y) of the CM, the underestimation of cost model will overvalue the cutback in time than the actual cutback. However, if the time sensitive factor (x) is increased beyond the cost factor (y) (see x^* in

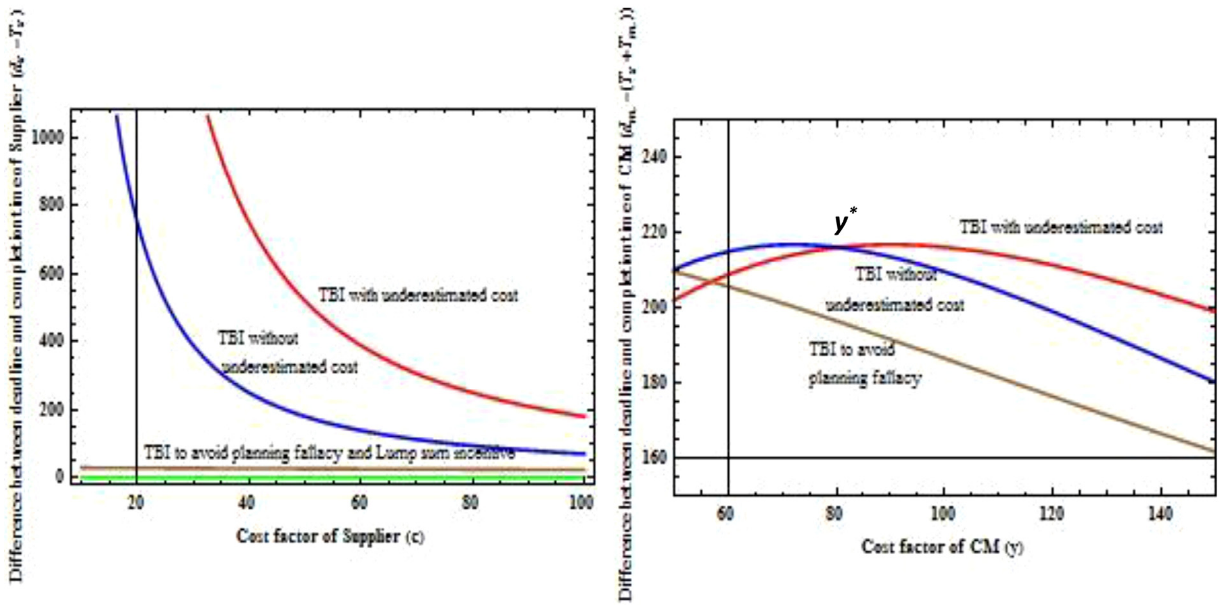

Figure 3 (a and b) Effect of cost factor for supplier and CM on the reduction of time.

Fig. 4b), then the underestimation of cost model will undervalue the cutback in time. Further, the difference between x and y alters the difference between deadline and completion time of CM. When the difference between x and y is higher, the gap between d_m and $T_s + T_m$ reduces and vice versa. Hence, it is better for the time sensitivity of the CM (x) to be less than the cost factor of the CM (y).

Fig. 5a also shows that the TBI model with underestimated cost dominates the TBI model without underestimation (similar to Figs. 3a and 4a), except that the difference between deadline and completion time for the supplier (cutback in time) increases as a function of supplier's bonus (b_s) respectively, whereas the cutback in time decreases as a function of cost. In the model for underestimation of cost, the increase in bonus for the CM (b_m) shows a slight decrease in the cutback, which contradicts the interpretation given by supplier for cutback in supplier time as a function of bonus for supplier. However, in the model to avoid planning fallacy (see dotted and dashed line in Fig. 5b), the increase in the bonus for the CM increases the reduction of time as per intuition. In Fig. 6a, it is shown that the reduction in time increases for an increase in the bonus for the OEM from the market for early availability of product (R). However, the bonus for the OEM follows the analytical interpretations (cutback in time is higher for underestimation of cost model than the actual cutback in time) only after a certain value,

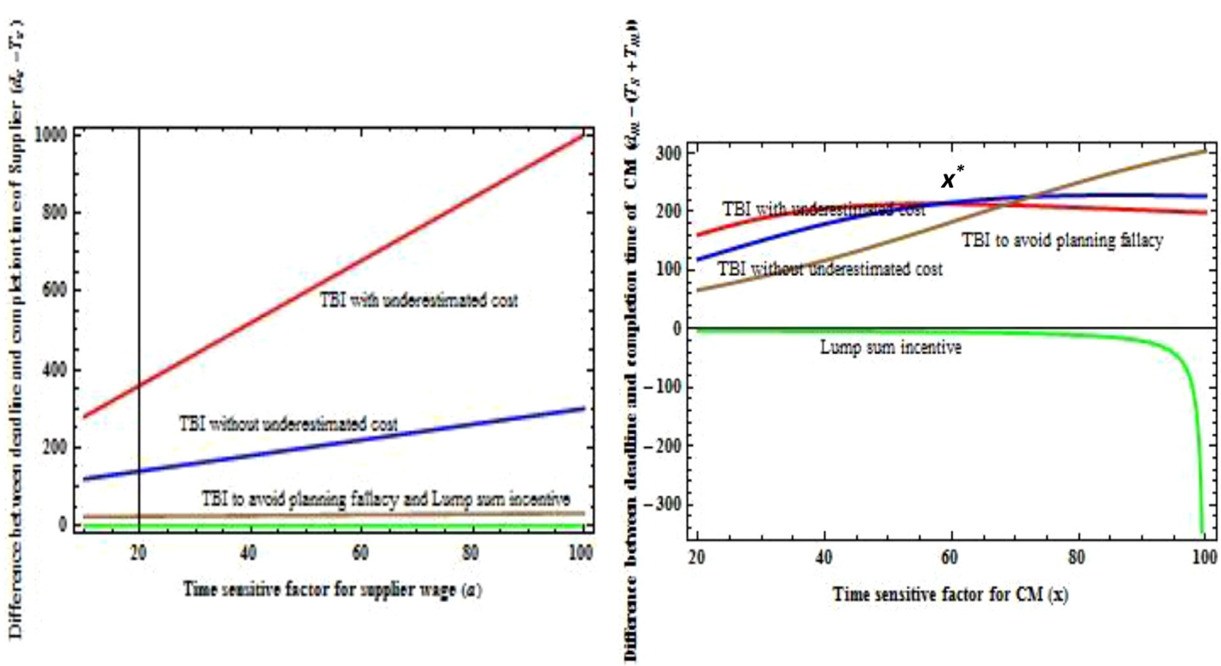

Figure 4 (a and b) Effect of time sensitive factor for supplier and CM on the reduction of time.

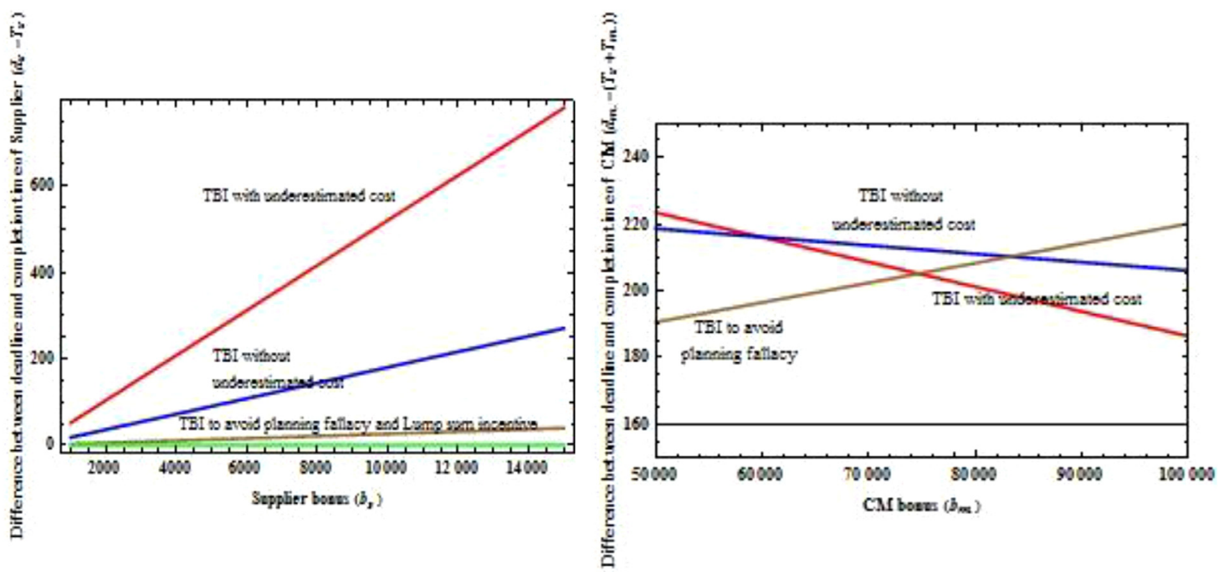

Figure 5 (a and b) Effect of bonus for supplier and CM on the reduction of time.

which illustrates that the bonus for the OEM does not influence the miscalculation of cutback in time. The cutback in time in case of a TBI model with underestimation is higher than the actual cutback in time as a function of cost coefficient of CM (q) as well (see solid line and dotted line in Fig. 6b).

Fig. 7a shows that the cutback in time (difference between deadline and completion time) is very high when the cost salience of the supplier (e) is less i.e. the underestimation of cost is high. This shows that being over-optimistic will overvalue the cutback in time, which is unrealistic. The model without underestimation of cost shows the actual reduction in time, which is less than in the model with underestimation of cost. However, the model to avoid planning fallacy will further decrease the difference between deadline and completion time, due to the addition of penalty for underestimation of cost. The difference between deadline and completion time is lesser (higher), when the underestimation of cost is higher (lesser) due to higher penalty for being over-optimistic. Fig. 7b depicts the cutback in time as a function of cost salience of the CM (f). The analytical result (the cutback time for underestimation of cost model is higher than the actual cutback time) is followed based on the gap (difference) between x, y and p. When the difference between each variable in the order $x > y > p$ is higher (lesser), the cutback in time for underestimation of cost model is higher (lesser) than the actual cutback in time. This principle is applicable only at a lesser value of cost salience (underestimation of cost is higher). Hence, even when the underestimation of cost is higher, when the difference between the variables x, y and p is less, the cutback in

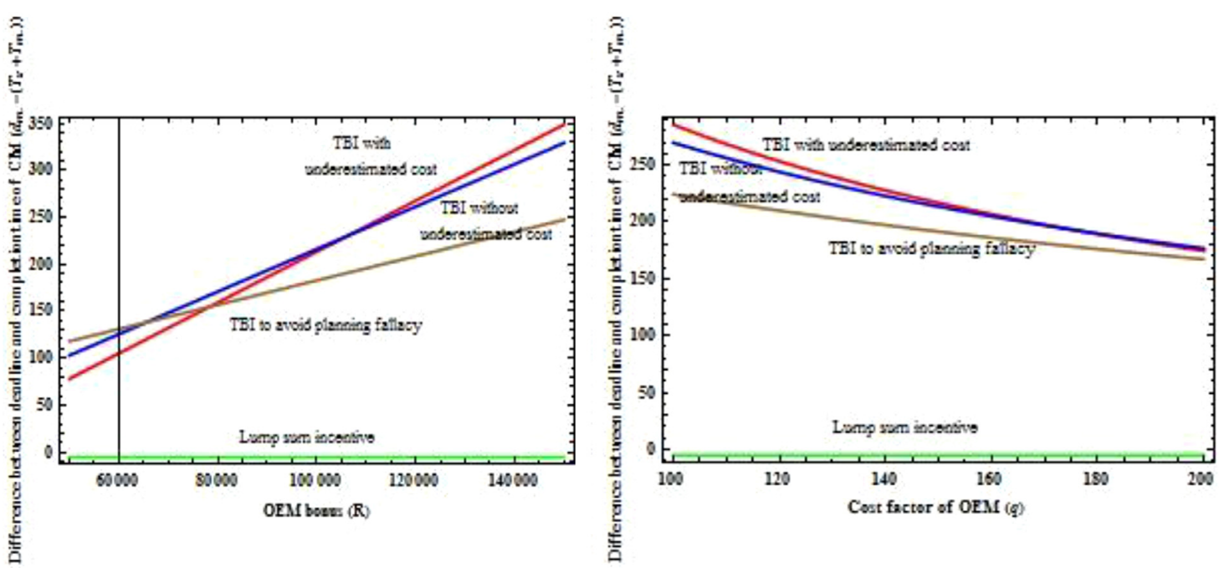

Figure 6 (a and b) Effect of bonus and cost of OEM on the reduction of time.

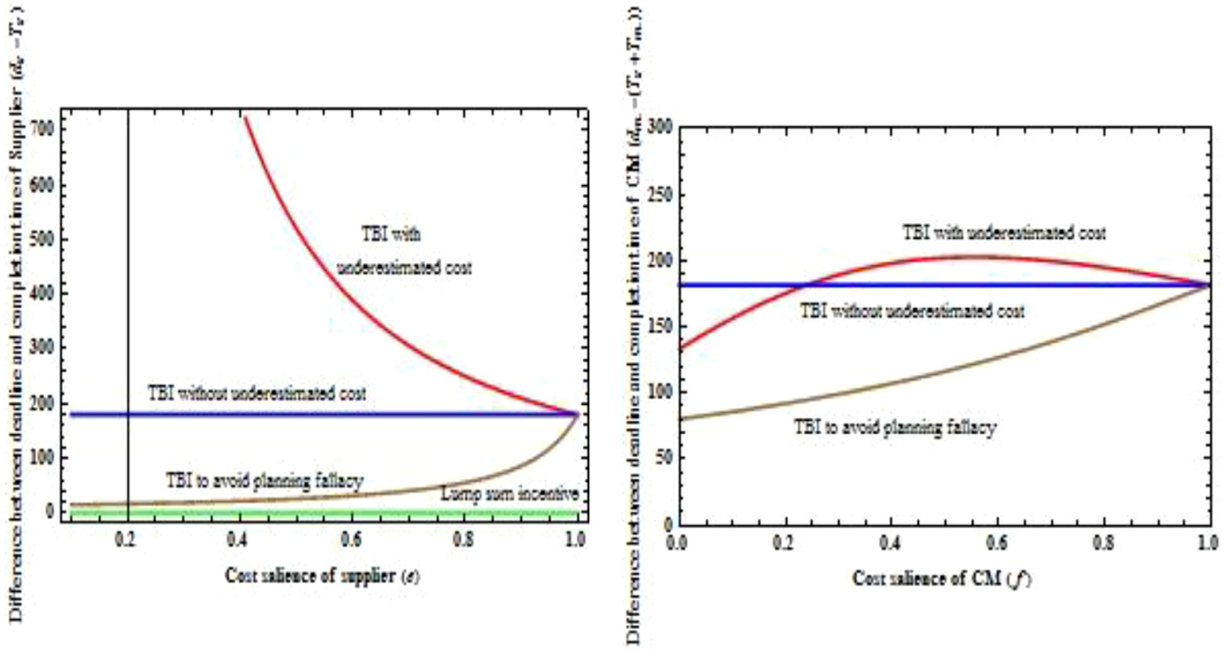

Figure 7 (a and b) Effect of cost salience for supplier and CM on the reduction of time.

time is not highly misjudged. However when the difference between these variables is less, the actual cutback in time is also increased.

Conclusions

We mathematically model a scenario in the manufacturing environment to avoid the planning fallacy of procurers (or the OEM) in a supply chain. In supply chain literature, the lead time is estimated by the provider (supplier / manufacturer), who is producing the product or offering the service. However, this prediction could be over optimistic as the provider is biased towards believing that a project will be easy to complete. To avoid this planning fallacy, the lead time can be estimated by the procurers (or the OEM) themselves primarily based on the wage and bonus offered.

From the results obtained for the threshold incentive model, we verify that the time taken to complete is always less than the deadline imposed on a player in the supply chain. In other words, the threshold incentives motivate the supplier and CM to mitigate planning fallacy and also achieve a "cutback in time". Further, we study the transformation of cutback in time (difference between deadline and completion time of a player) as a function of all parameters, and conclude that the threshold based incentives can help in completing the task before the deadline imposed by the downstream player. Further, we show the conditions under which the actual completion time is less than the deadline. Future research on this model could consider some of these parameters to be private information. The assumption that the time sensitive factor and cost parameters are common knowledge (information can be elicited from the past records) to all players can be relaxed, as the procurer (the OEM) may not get the information about all parameters, where private information can create another technical challenge for the OEM to design an effective contract considering the variables to be uncertain. A sensitivity analysis on the time sensitive and cost factors of all players can be done to analyse the impact of these factors on the performance of the model.

Appendix I

Lump sum incentive scheme

Uniqueness of Nash equilibrium for lump sum incentive scheme

Lemma 1. The supplier's profit function π_S is strictly concave w.r.t. T_s
Proof: The first-order and second order condition for the supplier's profit function, $\pi_s(T_s)$ are given as:

$$\frac{\partial(\pi_S)}{\partial T_s} = -c - 2aT_s - 2k_s(-d_s + T_s) + w_s = 0$$

$$\frac{\partial^2(\pi_S)}{\partial {T_s}^2} = -2a - 2k_s < 0$$

Hence, the supplier's profit function is concave w.r.t. T_s iff a and $k_s > 0$.

Lemma 2. The CM's profit function π_M is strictly concave w.r.t. d_s and T_m
Proof: The first-order and second order condition for the CM's profit function, $\pi_M(d_s, T_m)$ are given as:

$$\frac{\partial \pi_M}{\partial d_s} = -\frac{yk_s}{(a+k_s)} + \frac{ak_s(-c+2d_sk_s+w_s)}{2(a+k_s)^2} - \frac{xk_s\left(T_m + \frac{-c+2d_sk_s+w_s}{2(a+k_s)}\right)}{a+k_s} - \frac{2k_mk_s\left(-d_m + T_m + \frac{-c+2d_sk_s+w_s}{2(a+k_s)}\right)}{a+k_s} - \frac{k_s\left(w_s - \frac{a(-c+2d_sk_s+w_s)}{2(a+k_s)}\right)}{a+k_s} + \frac{k_s\left(w_m - x\left(T_m + \frac{-c+2d_sk_s+w_s}{2(a+k_s)}\right)\right)}{a+k_s} = 0$$

$$\frac{\partial \pi_M}{\partial T_m} = -y + w_m + 2x\left(T_m + \frac{-c+2d_sk_s+w_s}{2(a+k_s)}\right) - 2k_m\left(-d_m + T_m + \frac{-c+2d_sk_s+w_s}{2(a+k_s)}\right) = 0$$

$$H = \begin{bmatrix} \frac{\partial^2 \pi_M}{\partial {d_s}^2} & \frac{\partial^2 \pi_M}{\partial d_s\, \partial T_m} \\ \frac{\partial^2 \pi_M}{\partial T_m\, \partial d_s} & \frac{\partial^2 \pi_M}{\partial {T_m}^2} \end{bmatrix}$$

$$\frac{\partial^2 \pi_M}{\partial {d_s}^2} = \frac{{k_s}^2(2a-2x-2k_m)}{(a+k_s)^2} < 0$$

$$\frac{\partial^2 \pi_M}{\partial {T_m}^2} = -2x - 2k_m < 0$$

$$\frac{\partial^2 \pi_M}{\partial T_m d_s} = -\frac{2xk_s}{(a+k_s)} - \frac{2k_sk_m}{(a+k_s)}$$

$$\frac{\partial^2 \pi_M}{\partial d_s T_m} = -\frac{2xk_s}{(a+k_s)} - \frac{2k_sk_m}{(a+k_s)}$$

$$H = -\frac{4axk_s^2}{(a+k_s)^2} - \frac{4ak_mk_s^2}{(a+k_s)^2}$$

Hence, the OEM's profit function is concave w.r.t. d_m iff $p > x$.

Note 1: The difference between deadline (d_s) and the completion time of the supplier (T_s) in the lump sum incentive model is $\frac{c}{2k_s} > 0$. As explained in the article, the penalty for underestimation of cost (k_s) is higher than the cost coefficient (c) of supplier. Hence the cutback in time using lump sum mechanism is very close to zero. However, the difference between deadline and the completion time of the CM in the lump sum incentive model is $\frac{y(p-x)-pw_m}{2k_m(p-x)} < 0$, since the time sensitive factor of the OEM (p) is higher than the CM (x).

Appendix II

Threshold based incentive scheme

Uniqueness of Nash equilibrium for threshold based incentive without optimistic bias

Lemma 4. The supplier's profit function π_S is strictly concave w.r.t. T_s
Proof: The first-order and second order condition for the supplier's profit function, $\pi_s(T_s)$ are given as:

$$\frac{\partial(\pi_S)}{\partial T_s} = -\left(b_s - c(d_s - T_s)\right) + c(d_s - T_s) - aT_s + (-aT_s + w_s) = 0$$

$$\frac{\partial^2(\pi_S)}{\partial {T_s}^2} = -2a - 2c < 0$$

Hence, the supplier's profit function is concave w.r.t. T_s iff a and $c > 0$.

Lemma 5. The CM's profit function π_M is strictly concave w.r.t. d_s *and* T_m
Proof: The first-order and second order condition for the CM's profit function, $\pi_M(d_s, T_m)$ are given as:

$$\frac{\partial \pi_M}{\partial d_s} = \frac{acn(-b_s+2cd_s+w_s)}{2(a+c)^2} + c\left(1 - \frac{c}{a+c}\right)n\left(d_s - \frac{-b_s+2cd_s+w_s}{2(a+c)}\right) + \frac{cy\left(d_m - T_m - \frac{-b_s+2cd_s+w_s}{2(a+c)}\right)}{a+c} - \frac{cx\left(T_m + \frac{-b_s+2cd_s+w_s}{2(a+c)}\right)}{a+c} - \frac{cn\left(w_s - \frac{a(-b_s+2cd_s+w_s)}{2(a+c)}\right)}{a+c} - \left(1 - \frac{c}{a+c}\right)n\left(b_s - c\left(d_s - \frac{-b_s+2cd_s+w_s}{2(a+c)}\right)\right) - \frac{c\left(b_m - y\left(d_m - T_m - \frac{-b_s+2cd_s+w_s}{2(a+c)}\right)\right)}{a+c} + \frac{c\left(w_m - x\left(T_m + \frac{-b_s+2cd_s+w_s}{2(a+c)}\right)\right)}{a+c} = 0$$

Hence, the CM's profit function is concave w.r.t. d_s *and* T_m iff a, x, k_m *and* k_s are $>$ *0* such that the Hessian matrix is negative semi definite.

Lemma 3. The OEM's profit function π_O is strictly concave w.r.t. d_m
Proof: The first-order and second order condition for the supplier's profit function, $\pi_O(d_m)$ are given as:

$$\frac{\partial^2(\pi_S)}{\partial {d_m}^2} = -\frac{8a^2pk_m^2}{(2ax+2ak_m)^2} + \frac{8a^2xk_m^2}{(2ax+2ak_m)^2} < 0$$

$$\frac{\partial \pi_M}{\partial T_m} = -b_m + w_m + 2y\left(d_m - T_m - \frac{-b_s+2cd_s+w_s}{2(a+c)}\right) - 2x\left(T_m + \frac{-b_s+2cd_s+w_s}{2(a+c)}\right) = 0$$

$$H = \begin{bmatrix} \frac{\partial^2 \pi_M}{\partial {d_s}^2} & \frac{\partial^2 \pi_M}{\partial d_s\, \partial T_m} \\ \frac{\partial^2 \pi_M}{\partial T_m\, \partial d_s} & \frac{\partial^2 \pi_M}{\partial {T_m}^2} \end{bmatrix}$$

$$\frac{\partial^2\pi_M}{\partial {d_s}^2}=\frac{2ac^2}{(a+c)^2}-\frac{2c^2x}{(a+c)^2}-\frac{2c^2y}{(a+c)^2}<0$$

$$\frac{\partial^2\pi_M}{\partial d_s T_m}=-\frac{2cx}{(a+c)}-\frac{2cy}{(a+c)}<0$$

$$\frac{\partial^2\pi_M}{\partial {T_m}^2}=-2x-2y<0$$

$$H=-\frac{4ac^2x}{(a+c)^2}-\frac{4ac^2y}{(a+c)^2}$$

Hence, the CM's profit function is concave w.r.t. d_s *and* T_m iff a, c, x *and* y are >0 such that the Hessian matrix is negative semi definite.

Lemma 6. The OEM's profit function π_O is strictly concave w.r.t. d_m
Proof: The first-order and second order condition for the OEM's profit function, $\pi_O(d_m)$ are given as:

$$\frac{\partial^2(\pi_S)}{\partial {d_m}^2}=-\frac{2py^2}{(x+y)^2}+\frac{2xy^2}{(x+y)^2}-2q\left(1-\frac{y}{x+y}\right)^2<0$$

Hence, the OEM's profit function is concave w.r.t. d_m iff p, q , x and $y>0$ and $x<p, q$.

Note 2:

(1) The condition for deadline of the supplier to be higher than the completion time of the supplier in the threshold-based incentive model without optimistic bias, $\frac{(a+c)b_s}{2c^2}>0$, since $a, c, b_s>0$.
(2) The condition for deadline of the CM to be higher than the completion time of the CM in the model without optimistic bias is, $-\frac{-x(Rx+Vy)+(x^2-py+xy)b_m+pyw_m}{2\left(qx^2+(p-x)y^2\right)}>0$, since $p>y>x$, $R>b_m$, $V>w_m$ and x, y, p, q, R, V, b_m, $w_m>0$.

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Lemma 7. The supplier's profit function π_S is strictly concave w.r.t. T_s
Proof: The first-order and second order condition for the supplier's profit function, $\pi_s(T_s)$ are given as:

$$\frac{\partial(\pi_S)}{\partial T_s}=-b_s+2ce(d_s-T_s)+2(1-e)p_s(d_s-T_s)-2aT_s+w_s=0$$

$$\frac{\partial^2(\pi_S)}{\partial {T_s}^2}=-2a-2ce-2(1-e)p_s<0$$

Hence, the supplier's profit function is concave w.r.t. T_s iff a, c, e and $p_s>0$.

Lemma 8. The CM's profit function π_M is strictly concave w.r.t. d_s *and* T_m
Proof: The first-order and second order condition for the CM's profit function, $\pi_M(d_s, T_m)$ are given as:

$$\begin{aligned}\frac{\partial\pi_M}{\partial d_s}=&-\frac{b_m(ce+p_s-ep_s)}{\left(a+ce-(-1+e)p_s\right)}-\frac{(ce+p_s-ep_s)\left(w_s-\frac{a\left(-b_s+2d_s(ce+p_s-ep_s)+w_s\right)}{2\left(a+ce-(-1+e)p_s\right)}\right)}{a+ce-(-1+e)p_s}\\&+\frac{a(ce+p_s-ep_s)\left(-b_s+2d_s(ce+p_s-ep_s)+w_s\right)}{2\left(a+ce-(-1+e)p_s\right)^2}+\frac{2fy(ce+p_s-ep_s)\left(d_m-T_m-\frac{-b_s+2d_s(ce+p_s-ep_s)+w_s}{2\left(a+ce-(-1+e)p_s\right)}\right)}{a+ce-(-1+e)p_s}\\&-\frac{x(ce+p_s-ep_s)\left(T_m-\frac{-b_s+2d_s(ce+p_s-ep_s)+w_s}{2\left(a+ce-(-1+e)p_s\right)}\right)}{a+ce-(-1+e)p_s}-b_s\left(1-\frac{(ce+p_s-ep_s)}{\left(a+ce-(-1+e)p_s\right)}\right)\\&+\frac{2(1-f)p_m(ce+p_s-ep_s)\left(d_m-T_m-\frac{-b_s+2d_s(ce+p_s-ep_s)+w_s}{2\left(a+ce-(-1+e)p_s\right)}\right)}{a+ce-(-1+e)p_s}\\&+\frac{(ce+p_s-ep_s)\left(w_m-x\left(T_m+\frac{-b_s+2d_s(ce+p_s-ep_s)+w_s}{2\left(a+ce-(-1+e)p_s\right)}\right)\right)}{a+ce-(-1+e)p_s}=0\end{aligned}$$

$$\begin{aligned}\frac{\partial\pi_M}{\partial T_m}=&-b_m+w_m+2fy\left(d_m-T_m-\frac{-b_s+2d_s(ce+p_s-ep_s)+w_s}{2\left(a+ce-(-1+e)p_s\right)}\right)-2x\left(T_m+\frac{-b_s+2d_s(ce+p_s-ep_s)+w_s}{2\left(a+ce-(-1+e)p_s\right)}\right)\\&-2(1-f)p_m\left(d_m-T_m-\frac{-b_s+2d_s(ce+p_s-ep_s)+w_s}{2\left(a+ce-(-1+e)p_s\right)}\right)=0\end{aligned}$$

$$H=\begin{bmatrix}\frac{\partial^2\pi_M}{\partial {d_s}^2} & \frac{\partial^2\pi_M}{\partial d_s\,\partial T_m}\\ \frac{\partial^2\pi_M}{\partial T_m\,\partial d_s} & \frac{\partial^2\pi_M}{\partial {T_m}^2}\end{bmatrix}$$

$$\frac{\partial^2 \pi_M}{\partial {d_s}^2} = \frac{2a(ce+p_s-ep_s)^2}{\left(a+ce-(-1+e)p_s\right)^2} - \frac{2x(ce+p_s-ep_s)^2}{\left(a+ce-(-1+e)p_s\right)^2} - \frac{2fy(ce+p_s-ep_s)^2}{\left(a+ce-(-1+e)p_s\right)^2} - \frac{2(1-f)p_m(ce+p_s-ep_s)^2}{\left(a+ce-(-1+e)p_s\right)^2} < 0$$

$$\frac{\partial^2 \pi_M}{\partial {T_m}^2} = -2x - 2fy - 2(1-f)p_m < 0$$

$$\frac{\partial^2 \pi_M}{\partial T_m d_s} = -\frac{2x(ce+p_s-ep_s)}{a+ce-(-1+e)p_s} - \frac{2fy(ce+p_s-ep_s)}{a+ce-(-1+e)p_s} - \frac{2(1-f)p_m(ce+p_s-ep_s)}{a+ce-(-1+e)p_s} < 0$$

$$\frac{\partial^2 \pi_M}{\partial d_s T_m} = -\frac{2x(ce+p_s-ep_s)}{a+ce-(-1+e)p_s} - \frac{2fy(ce+p_s-ep_s)}{a+ce-(-1+e)p_s} - \frac{2(1-f)p_m(ce+p_s-ep_s)}{a+ce-(-1+e)p_s} < 0$$

$$H = -\frac{4a\left(x+fy-(-1+f)p_m\right)\left(ce-(-1+e)p_s\right)^2}{\left(a+ce-(-1+e)p_s\right)^2}$$

Hence, the CM's profit function is concave w.r.t. d_s *and* T_m iff a, c, x *and* y are > 0 such that the Hessian matrix is negative semi definite.

Lemma 9. The OEM's profit function π_O is strictly concave w.r.t. d_m
Proof: The first-order and second order condition for the OEM's profit function, $\pi_O(d_m)$ are given as:

$$\frac{\partial^2(\pi_S)}{\partial {d_m}^2} = -\frac{2p\left(fy-(-1+f)p_m\right)^2}{\left(x+fy-(-1+f)p_m\right)^2} + \frac{2x\left(fy-(-1+f)p_m\right)^2}{\left(x+fy-(-1+f)p_m\right)^2} - 2q\left(1-\frac{fy-(-1+f)p_m}{x+fy-(-1+f)p_m}\right)^2 < 0$$

Hence, the OEM's profit function is concave w.r.t. d_m iff p, q, x and $y > 0$, $f < 1$, and $x < p, q$.

Note 3:

(1) The condition for deadline of the supplier to be higher than the completion time of the supplier in the model to mitigate planning fallacy is, $\frac{b_s\left(a+ce-(-1+e)p_s\right)}{2\left(ce-(-1+e)p_s\right)^2} > 0$, since $e < 1$ and $a, c, e, b_s, p_s > 0$.

(2) The condition for deadline of the CM to be higher than the completion time of the CM in the threshold-based incentive model to mitigate planning fallacy is,

$$-\frac{Rx^2 - fVxy + b_m\left(x^2 - fpy + fxy + (-1+f)(p-x)p_m\right) + fpywm + (-1+f)p_m(Vx - pw_m)}{2\left(qx^2 + f^2(p-x)y^2 - 2(-1+f)f(p-x)p_m + (-1+f)^2(p-x){p_m}^2\right)} > 0,$$

since $p > y > x$, $R > b_m$, $V > w_m$ and x, y, p, q, R, V, b_m, $w_m > 0$.

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