

Psychological Safety and Group Learning: Cycle-Time Reduction for Collaborative Product Development

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Abstract

This study presents a System Dynamics (SD) analysis of collaborative product development in a manufacturer-supplier dyad. We conduct a SD-based case study in Taiwan high-tech electronics where a manufacturer and a supplier form vertical product development partnerships. The SD inquiry helps inter-organizational project teams understand how cognitive and social factors such as psychological safety, level of collaboration, and group learning rather than technical factors such as the deployment of collaboration software affect the development cycle-time more. Simulation results show that higher initial level of psychological safety and of manufacturer-supplier collaboration contributes to cycle-time reduction. The highest level of both factors generates a two-stage growth mode of psychological safety that has not been seen in literature, but does not lead to most group learning activities all the time. Further, project teams exhibit poorer group learning and fail to attain cycle-time reduction when they merely set up higher performance goals without enhancing initial level of collaboration and of psychological safety.

Key words: behavioral operations, collaborative product development, group learning, psychological safety, simulation, system dynamics.

1. Motivation and Overview

The concept of Collaborative Product Development (CPD) has emerged over recent decades with the growing popularity of product development across organizational boundaries (Eynard and Yan, 2008). CPD is “a business strategy, work process and collection of software applications that facilitates different organizations to work together on the development of a product” (Wikipedia, 2009). At the strategic level, manufacturers use CPD to align suppliers and customers in order to reduce development cycle-time and create competitive advantage (Mishra and Shah, 2009). At the operational level, CPD facilitates the sharing of resources among distributed actors and activates the collaboration of virtual teams in a web-based environment (Wang et al., 2008).

In the context of CPD, inter-organizational project teams have real-time access to engineering information and thus work in a more informed fashion. The members of project teams communicate with one another to modify the sketches of products via the internet (Büyüközkan et al., 2007). They use collaboration software to share engineering information, access design resources, monitor development progress, and control the project. Such an extensive use of collaboration software and appropriate technologies to support the needs of people, organizations, and data also distinguishes CPD from the widely-used concurrent engineering approach.

Although empirical evidence shows that the effective use of collaboration software saves much time in communication (Banker et al., 2006), its effect on improving the productivity of inter-organizational product development teams has been mixed (Bardhan et al., 2007). Boehm and Turner (2005) claim that the introduction of agile process and collaboration software often causes conflicts in product development organizations when agile processes are merged with standard industrial processes, project management practices, and the work habits of engineers.

Some researchers have examined the collaboration of inter-organizational project teams in a manufacturer-supplier dyad and agree that CPD reduces project duration and enhances mutual learning. (Jassawalla and Sashittal, 1998; Corswant and Tunalv, 2002; Hoegl and Wagner, 2005). Nonetheless, Bstieler and Hemmert (2009) argue that these collaborations can encounter difficulties because partners possessing heterogeneous mind-sets and different expertise often hinder the effectiveness of using the collaboration software to reduce development cycle-time. In line with Krishnan and Ulrich (2001), they further claim that the process, mechanisms, and dynamics that may improve or harm performance in CPD are not well understood and that researchers should cast light on inter-organizational project teams.

To fill in the gap, we attempt to build a System Dynamics (SD) model to explore CPD. Grobler et al. (2008) suggest that modelers use qualitative methods such as a grounded theory approach to support building simulation models. A prototypical example for this kind of work appears in Oliva and Sterman (2001). They combine of a case study with an SD model to describe unanticipated effects of schedule pressure on quality erosion. Following the exemplar of combining quantitative and qualitative methods, we make complementary use of case studies and interviews (Yin 1994). We conduct expert interviews and collect data of CPD projects from a high-tech company in Taiwan. By doing so, we aim to enhance the usefulness of the SD model and to generate insights from reality.

The company, an innovative manufacturer specializing in design and manufacturing of thermal fans for electronic products, introduced collaboration software to foster *vertical product development partnerships* with a supplier, a tooling company. Vertical partnerships are project-based collaborations between a manufacturer and a supplier to fulfill missions (Anderson and Narus, 1990). In this case, the manufacturer and the supplier work closely on a CPD team to facilitate communication and to minimize the risks of designing a product or a critical component that is difficult to manufacture. A CPD team also allows them to take

advantage of the capabilities and resources of the partner to create synergy.

While there is increasing evidence that forming vertical partnerships in product development is important, there is also evidence that not all such efforts are successful (Wagner and Hoegel, 2006). This is also the issue that the manufacturer and the supplier have confronted in CPD. By pooling resources and deploying IT in development projects, the two partnering firms expect to reduce development cycle-time. Although they have installed advanced technologies and have resolved technical issues, they still have failed to achieve the expected time-efficiency (e.g. shorter time-to-market and time-to-volume).

Figure 1 illustrates the gap between the actual and the expected project duration after the implementation of CPD. The existence of the gap in time-reduction certainly surprised the chief R&D officer of the company. Even though the manufacturer followed “the best practices of CPD” claimed by the IT vendor (Smith, 2008), the vertical partnerships could not generate the agile development process needed to reduce the project duration. We wondered why such a diligent team could fail to harness collaborative technologies to achieve time efficiency.

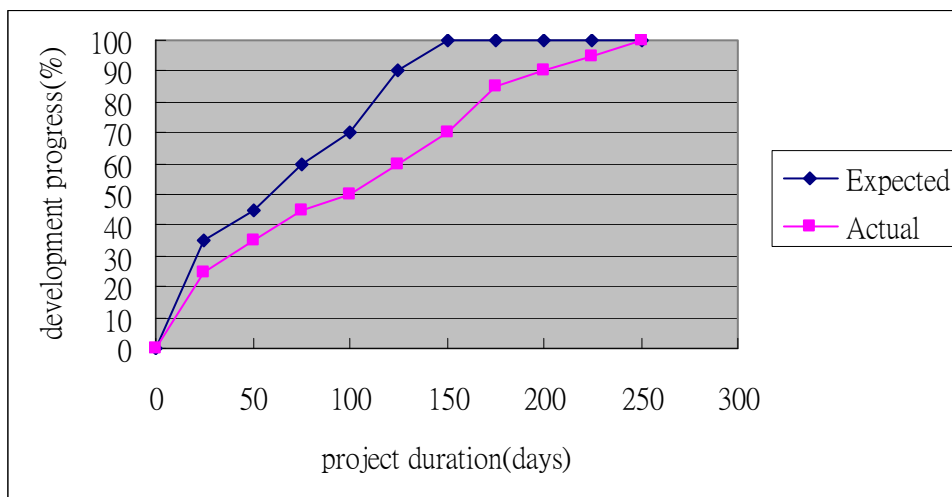


Figure 1: The gap of time efficiency

Such empirical irregularities motivated us to seek for theoretical explanations. After group meetings and a thorough discussion with the R&D chief officer, we suspected that

cognitive and social factors are the missing elements. For the manufacturer and the supplier who both have a heritage of outstanding technical and engineering achievement, behavioral considerations in CPD processes were neither familiar nor never well-understood. Bstieler and Hemmert (2009) argue that the management researchers still know too little about the psychological factors that generate dynamic behaviors and affect project duration in high-tech CPD teams. Therefore, we carefully analyze *psychological safety* and *group learning*, which are determinants of the effectiveness of teams (Kozlowski and Ligen, 2006). A primary goal of our study is to shed light on the human factors that are particularly important to catalyze productive vertical partnerships.

Bstieler and Hemmert (2009) present a *descriptive theory* (Carlile and Christensen, 2005) about psychological safety, team learning, and governance mechanisms that can assist CPD. They examine closely those factors by using multiple regression models but can merely conclude that the factors are positively *correlated* to time efficiency. It is surprising that researchers have yet to explore the *causal* relationships between antecedents and consequences. Our study aims establish a theory explaining how behavioral factors drive CPD performance. A well-developed theory is powerful because it advances state-of-the-art knowledge and helps managers understand cause-and-effect more in practical operations. Thus, we expect to provide causal explanations and propositions for normative theory development by tackling a SD-based simulation study, since we can harness simulation to design creative experimentation to produce novel theory (Davis et al. 2007).

2. Theoretical Background

In this section we briefly review the literature regarding behavioral operations, psychological safety, and group learning. We point out the gaps in existing literature and specify how an SD approach can fill in these gaps and enhance our understanding.

2.1 Behavioral Operations

Behavioral operations is defined as the study of human behavior and cognition and their impacts on operating systems and processes (Gino and Pisano, 2008). Gino and Pisano (2008) argue that human behavior may significantly affect how operating systems perform and how they respond to policy design and managerial interventions. However, confined to human beings are confined to *bounded rationality* and have limited abilities to process information (Simon, 1991). So, instead of assuming that people who participate in operating systems are fully rational, behavioral operations treats human behavior as an irrational and unstable factor which is determinant to the performance of operating systems.

Bendoly et al. (2006) claim that understanding human behavior is critical to the success of techniques and the adequacy of theories in Operations Management (OM). Therefore, a thorough examination of behavioral factors helps explain what causes the differences between organizations' operational performance. The differences in general cannot be explained by most formal models (Gino and Pisano, 2008). The inabilities of OM models to explain irrational human behavior are attributed to bounded rationality, which also constitutes the underlying assumption of SD (Lane and Oliva, 1998). An SD approach is instrumental in analyzing complex OM issues from behavioral perspectives (Repenning and Sterman, 2002). Thus, we harness the strength of SD to explore behavioral factors and to contribute to the development of behavioral theories in OM.

Gino and Pisano (2008) claim that behavioral theories are able to offer explanations for empirical irregularities that the theoretical lenses in other domains tend to view as anomalies.

For example, Boudreau et al. (2003) demonstrate how human resources management theories can bring behavioral insights into OM models and nurture the development of OM theories. Seeing the explanatory power of behavioral theories, we argue that the complexity of CPD can be better elucidated from a behavioral perspective. An inter-organizational CPD team is a complex technical and social system in which human behavior and group learning are central drivers to process reengineering and conflict resolution (Lam and Chin, 2005; Bstieler and Hemmert, 2009). In our article, instead of technical factors such as the implementation of collaboration software and the integration of enterprise information systems, social and cognitive factors such as psychological safety and group learning are key drivers of team productivity and time efficiency. Both factors are discussed in the next two sections.

2.2 Psychological Safety

Gino and Pisano (2008) identify *OM-specific studies* as an opportunity for behavioral operations. Their main purpose is to uncover new social or cognitive factors that arise in OM contexts to develop or refine behavioral theories. Edmonson's work on psychological safety is an example of this type of research. Edmonson (1999) defines *psychological safety* as "a climate-like shared belief among team members that the team is a safe context for interpersonal risk taking." In other words, psychological safety is a team-level construct representing a sense of confidence that the work group or team will not embarrass or punish a member for expressing her thoughts truthfully. The team perception of psychological safety is essential for CPD team members to express truthful ideas that are critical to facilitate the concept development and to identify potential flaws of product design and development in the on-line co-review platform.

Moreover, psychological safety facilitates group learning behavior because it reduces an individual's concern about being embarrassing or threatening while she speaks up about

doubts, questions, and mistakes (Edmondson, 1999). Carmeli et al. (2009) claim that perceptions of being psychologically safe alleviate these concerns and encourage group learning behaviors such as feedback seeking, boundary spanning, and innovation. However, Edmondson finds that when people seek feedback they also put themselves at risk of being criticized. Members in a team who feel psychologically safe are more willing to ask for help and engage in learning. The bias is uncovered in the operating context of small work teams ranging from surgery, nursing, production, and management (Edmondson, 2004). Gino and Pisano (2008) claim that such a newly identified bias could affect OM settings more generally. Thus, we decide to analyze psychological safety in a high-tech CPD team.

Some people may argue that psychological safety is a construct similar to trust. However, Edmondson (2004) proposes that psychological safety distinguishes itself from trust in terms of the object of focus, time-frame, and level of analysis. While trust has widely appeared in organizational and operational studies on product development teams (Bstieler, 2006), Edmondson (2004) argues that the role of psychological safety in IT-enabled dispersed or virtual teams may be very different and that future research is needed to investigate this area. Although intangible elements such as trust and psychological safety are hard to measure, Luna-Reyes et al. (2008) successfully use an SD approach to quantify the effects of trust and knowledge sharing in a collaborative team. Inspired by their work, we apply Edmondson's psychological lenses to penetrate the CPD team and set up an SD model to simulate the development cycle-time.

2.3 Group Learning

Senge (1990) emphasizes the value of group learning and of using systems thinking to help organizations achieve sustained effectiveness. Generally, CPD teams have to execute highly intelligence-oriented tasks. Thus, learning is indispensable to enable groups to acquire

new skills, improve processes, and find new ways of working. The model proposed by Edmonson (1999) presents group learning as a process consisting of three basic elements, *antecedent conditions*, *team beliefs*, and *team learning behavior*. Edmonson's model is widely used in organizational studies, but it does not explicitly show the interrelations of the various variables that influence the effectiveness of group learning (Lizeo, 2005). Most of the subsequent studies have addressed the factors separately. Thus, Kozlowski and Ilgen (2006) argue that there has been relatively little research to specify the process of team learning. In the rest of this proposal, *team learning* and *group learning* are used interchangeably.

The team learning process includes activities such as sharing information, experimenting, asking for help, and discussing errors. These learning activities have the potential to create a positive change and to influence team productivity and performance (Edmondson, 2004). Additionally, Akgun et al. (2002) and Edmondson and Nembhard (2009) argue that more studies on how team learning varies over different stages of product development processes and different environmental conditions are needed. To bridge the gap, this study applies an SD approach to set up an integrated model to explore the interactions between the factors fostering group learning in CPD. By running simulation experiments, we expect to present a dynamic theory that is capable of explaining how learning behaviors change over time.

While contemporary product development activities are closely related to team learning and creating superior customer solutions through the learning process (Akgun et al., 2002; Bstieler and Hemmert, 2009), *Learning by doing* is a critical enabler on which the manufacturer and the supplier both rely to improve operational performance. For a product design and development group, learning by doing can be translated into innovative products and solutions for partners or customers. For a process development and production group, learning by doing decreases production errors and contributes to a faster ramp-up (Terwiesch and Boch, 2001). Learning by doing helps groups execute projects in such ways to deliver

creative and high quality products faster. We suggest that learning by doing is critical to promote the effect of group learning in collaborative working environments and follow the way Luna-Reyes et al. (2008) model learning by doing in collaborative processes.

Kozlowski and Ilgen (2006) argue that group learning is a dynamic process of interaction among team members. Therefore, our study uses an SD approach to better understand how group learning evolves over time. In addition, recent studies (Carmeli, 2007; Bstieler and Hemmert, 2009; Carmeli et al., 2009) confirm that psychological safety is positively related to group learning. However, their model merely captures the relationships between psychological safety and group learning from a static point of view. We believe that the accumulation of psychological safety in itself is a dynamic behavioral process as well. Empirically, factors such as leadership skills and emotional contagion influence the level of psychological safety either positively or negatively. In consequence, psychological safety changes over time and can be better understood from an SD perspective. In a nutshell, the inter-organizational project team forming to execute CPD is a complex feedback system that lends itself to an SD analysis.

3. A Dynamic Model

3.1 Dynamic Hypothesis

Figure 2 illustrates the research framework widely used in studies on psychological safety and group learning. Many researchers hypothesize the relationships among psychological safety, group learning, and development time shown in figure 2. With statistical significance, they report that psychological safety is positively related to group learning, which is subsequently positively related to time efficiency (e.g. Bstiler and Hemmert, 2009). In other words, theoretically psychological safety has second-order (indirect) effects on cycle-time reduction. Such effects are mediated by group learning. As for the question mark we put in figure 2, none of the foregoing studies has investigated the first-order (direct) effect of psychological safety on cycle-time reduction. However, the effect can be tested by using a simple regression. Our goal is to articulate the feedback mechanisms and formulate dynamic hypotheses instead of merely illustrating these single link relationships shown in figure 2.

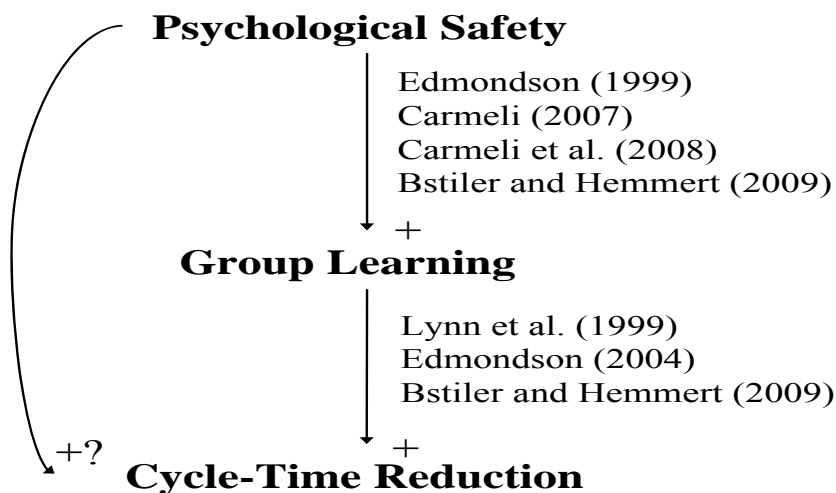


Figure 2: A common research framework

Both Edmondson (2004) and Bstieler and Hemmert (2009) claim that high psychological safety is a double-edged sword within a small work group because it may lead to lengthy discussions. While long discussions may be beneficial for enhancing mutual learning, they

consume time and potentially result in project delays. Hence, the two studies do not predict that psychological safety will produce higher or lower time efficiency. Nonetheless, in this case psychological safety is crucial for a high-tech design and manufacturing team to build confidence. As team members become more confident and comfortable in jointly working, they are more motivated and satisfied with the product they are working on. Then they are more willing to initiate improvement activities that build up psychological safety and contribute to group learning.

We also expect that when team members feel safe to express views in the on-line platform, they would exchange ideas immediately and communicate efficiently. Hence, lengthy discussions would seldom happen. As the CPD team gradually builds psychological safety, the *team commitment* to the product concept goes up and the *co-review duration* goes down. Shortening co-review duration is desirable because every task needs to go through the co-review stage before it is officially approved by the manufacturer and supplier. Therefore, we hypothesize that psychological safety not only stimulates group learning but also contributes to cycle-time reduction in terms of co-review duration, which can be calibrated based on project data and modeled as a non-linear function of psychological safety.

We herein form two causal loop diagrams (CLDs) that provide a rich description of feedback structures in the CPD process. By tracing through the CLDs, we articulate dynamic hypotheses as well. The two CLDs containing feedback loops in CPD are the building blocks of the SD model. Depicting a CLD helps modelers map the feedback structures made up of causal relationships between system elements. Figure 3 shows key symbols in a CLD.



Figure 3: Causal notations in the CLD

The positive sign in the left of figure 3 represents a positive causal relationship between X and Y. It means that if X increases, all things except X and Y being equal, Y will increase as well. The negative sign in the right of figure 3 represents a negative causal relationship between X and Y. It indicates that if X decreases, all things except X and Y being equal, Y will decrease as well.

The first CLD (see figure 4) illustrates the feedback structure of CPD workflow. The workflow starts from the stock *CPD Tasks to Do*. As the project advances, both *flawless working rate* and *flawed working rate* increase. The former delivers tasks without defects and the latter transmits tasks that need to be redone. Eventually both rates merge into *Non-Defective Tasks in review*, which has a *releasing rate* flowing into *CPD Tasks Released*. As the number of released tasks increases, the initial *CPD Tasks to Do* is depleted.

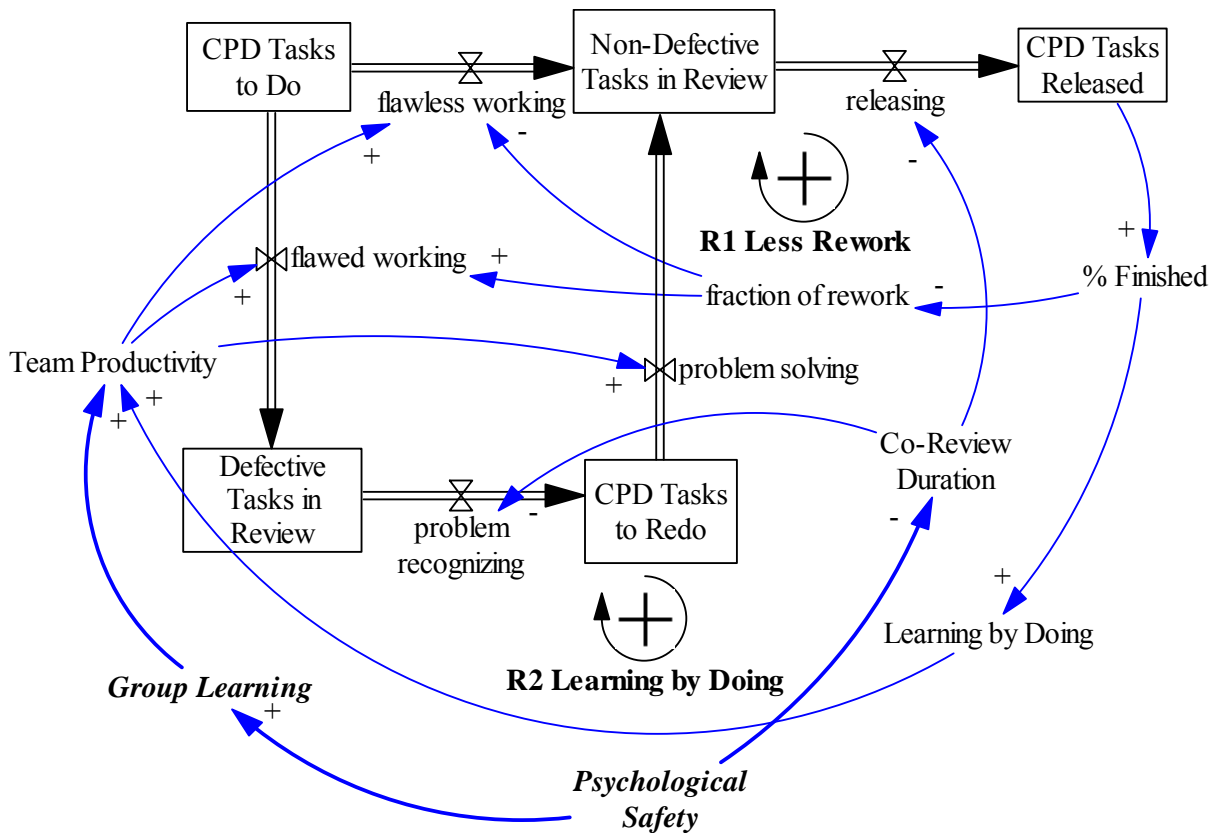


Figure 4: The feedback structure of CPD workflow

In figure 4, a reinforcing loop, *Less Rework* (R1) forms within CPD teams. The idea is that when *CPD Tasks Released* increases, *% finished* goes up. The project uncertainty decreases and engineers have more substantive accomplishments. As a result, *fraction of re-work* decreases and the tasks flow through each stage even faster. Another reinforcing loop *Learning by Doing* (R2) arises in CPD workflow. It arises while tasks are being finished and *Team Productivity* increases. As a result, the team has faster working rates and time efficiency increases. In the bottom of figure 4, we identify two elements, *Psychological Safety* and *Group Learning*. *Co-Review duration* decreases when *Psychological Safety* increases. *Team Productivity* increases with *Group Learning*. However, only the description of CPD workflow is not sufficient in clarifying the behavior dynamics induced by psychological safety and group learning, so we form the second CLD that illustrates the social-psychological factors in CPD process (see figure 5).

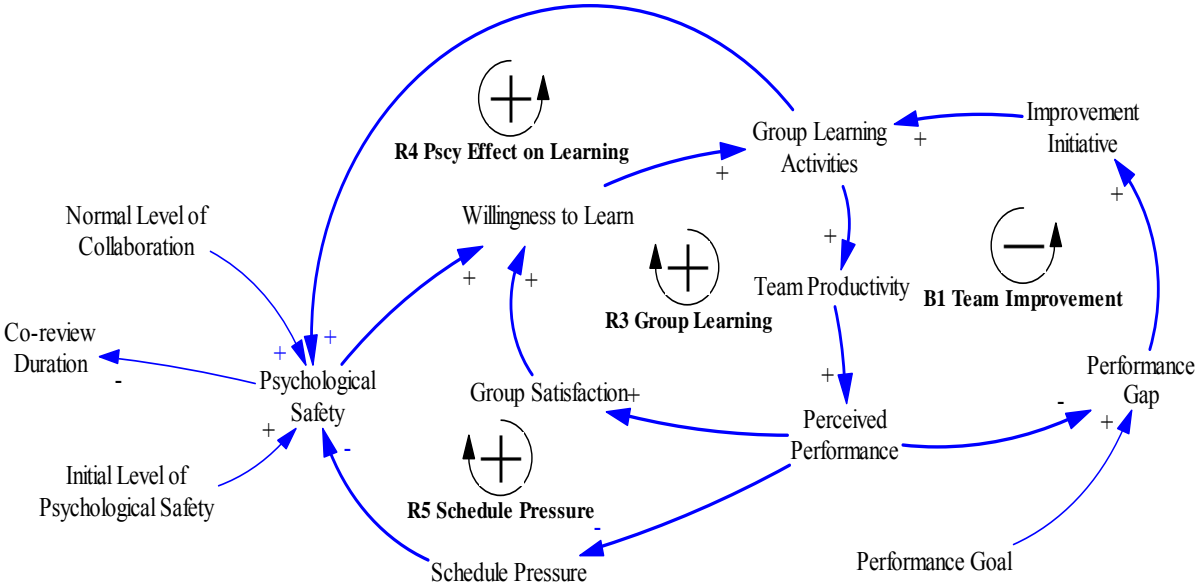


Figure 5: The feedback structure of socio-psychological factors in CPD

We start from a reinforcing loop, *Group Learning* (R3), in which more *Group Learning Activities* enable higher *Team Productivity*. As productivity increases, *Perceived Performance* and *Group Satisfaction* go up. Then team members have more *Willingness to Learn* and

initiate more *Group Learning Activities*. As we stated before, psychological safety causes more team learning. In the second reinforcing loop, Psychological Effect on Learning (R4), higher *Psychological Safety* makes engineers feel safe to ask and contribute their ideas for collective tasks. Therefore, *Willingness to Learn* and *Group Learning Activities* increase. As the development progress advances, *Group Learning Activities* represent that team members gain more experience and knowledge. Then they feel achieving more group process improvement of CPD activities and the improvement further increases *Psychological Safety*.

The last reinforcing loop we specify is Schedule Pressure (R5) in which *Schedule Pressure* increases with *Perceived Performance* but moves opposed to *Psychological Safety*. We also identify two organizational context related factors. The organizational context refers to organizational culture, rewards system, IT deployment, resource allocation, group/task design, and leader support. The contextual factors are *Normal level of manufacturer-supplier collaboration* and *Initial level of psychological safety*. The former reflects the level of collaboration required of both parties to foster co-development and the latter reflects the group atmosphere that influences the job-processing. Besides, more *Psychological Safety* stimulates higher product concept commitment and communication frequency (Burchill and Fine, 1997). According to theory and practice, the two elements enhancing the efficiency of co-development are essential for reducing *Co-review Duration* in this case.

Although we believe the three reinforcing loops together enhance time efficiency and group learning of CPD, such improvement has its limits and it is constrained by a balancing loop, Team Improvement (B1). As *Team Productivity* goes up, the task completion rate becomes faster and *Perceived Performance* increases, too. As the *Perceived Performance* reaches the *Performance Goal* set by the project leader, the *Performance Gap* decreases. Under such circumstances, the CPD team has less *Improvement Initiate*. As a result, *Group Learning Activities* decrease and *Team Productivity* increase at a much slower rate as well.

Psychological Safety and *Group Learning* may become stationary after the *Performance Goal* is achieved in loop B1.

In fact, many high-tech companies initialize improvement programs as B1 depicts. They also recognize the side-effects of schedule pressure in R5. However, most of them fail to specify behavioral factors driving team performance shown in R3 and R4. We argue that, without the mediating effects brought by the social and cognitive factors we have identified, cycle-time reduction cannot be realized by merely deploying collaboration software to strengthen Team Improvement.

As we go through feedback loops and depict dynamic hypotheses, we head to build the simulation model. Before doing that, we need to clarify two underlying assumptions in our model. First, there are no hiring and training considerations in this particular case. The nature of the development project presented in this article is different from the construction project, which is labor- and capital-intensive and involves frequent hiring and training. In contrast, the manufacturer and the supplier always try to keep the workforce stable and seldom hire or fire engineers for a certain project. Second, to limit the scope of our paper, our model does not consider the impact of leader skills on team members' behaviors. Sarin and McDermott (2003) examine how leadership characteristics in cross-functional new product development teams affect the learning, knowledge application, and the performance of these teams. Subsequent studies should clarify the effect of leader characteristics on internal dynamics of CPD teams.

3.2 Model Structure

According to the foregoing CLD, we then formulate a simulation model. The model is composed of two sectors, the *workflow sector* and *psychological safety and group learning sector*. The workflow sector we build here is similar to the stock and flow structure commonly used in project management modeling (Lyneis and Ford, 2007). Nevertheless, in order to

clearly delineate the vertical development partnerships, we model the workflow of both parties separately. In figure 6, the upper side exhibits the workflow in the manufacturer’s site and the lower side exhibits workflow in the supplier’s site. This sub-model is built according to the feedback structure of CPD work shown in figure 4.

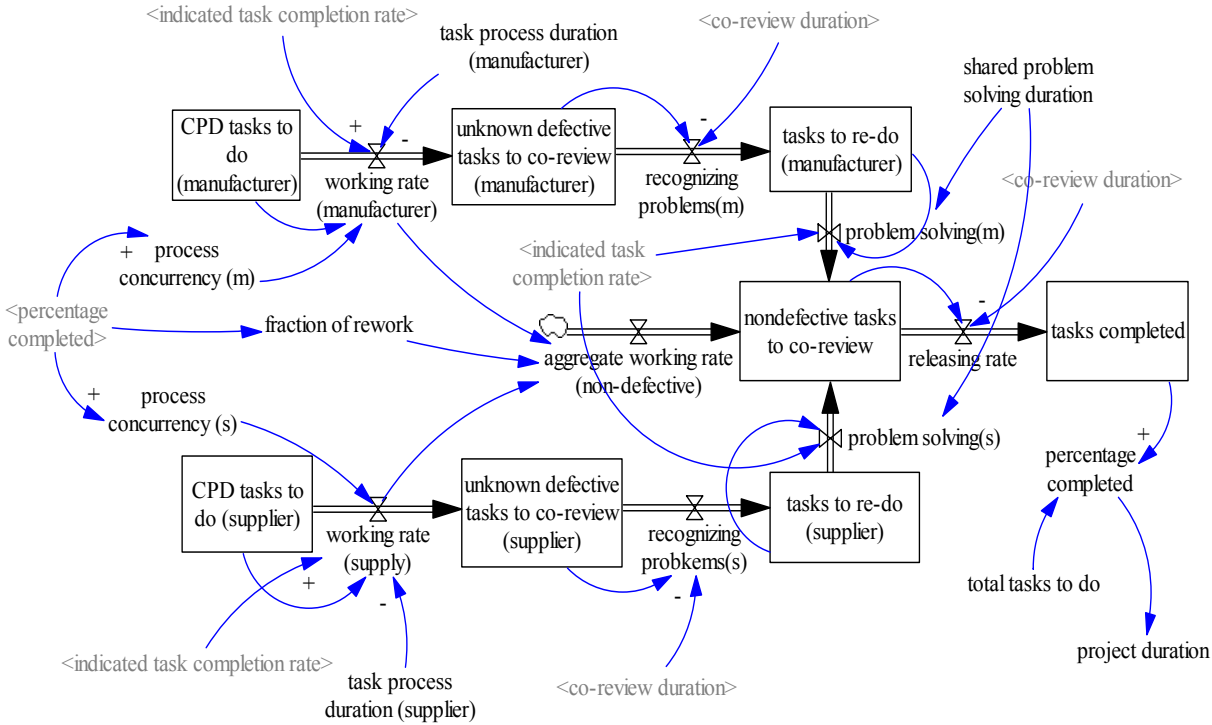


Figure 6: The workflow sector

In the CPD context, the major change in product development process is that the tasks done by both the manufacturer and the supplier flow into the co-review stock, named *non-defective tasks to co-review*. That is an important characteristic of CPD process. As the development project advances, the information related to finished tasks will be uploaded on to the web-based product data management systems by the manufacturer and the supplier respectively. Then the engineers and managers of both parties can log on to the on-line co-review platform to check and modify the development related tasks. The checked tasks eventually flow into the stock called “*tasks completed*” in the right side of figure 6.

Equations of the workflow sub-model can be found in Appendix A. The physics of our

model are grounded on two validated SD models targeting at concurrent product development process (Ford and Sterman, 1998; Lin et al., 2008). We elicit expert opinions from the R&D chief officer to identify the collaborative workflow, to set up the parameters, and to delineate non-linear relationships. By working with an industrial expert and referring to existing models, our model is soundly grounded in empirical work and its validity is strengthened.

In addition to the workflow sector, figure 7 is a manifestation of psychological safety and group learning sector in our model. However, unlike the work flow sector that is built upon several validated models and contains elements comparatively easier to quantify, this sector is a quite abstract model because psychological safety and group learning deals with mental beliefs that are difficult to measure. Although this sub-model is theory-driven, such a modeling effort enhances our understanding of soft concepts by operationalizing them in a CPD model. Sastry (1997) illustrates how one can formulate a theory-driven SD model without using empirical data to validate but still can get concrete findings.

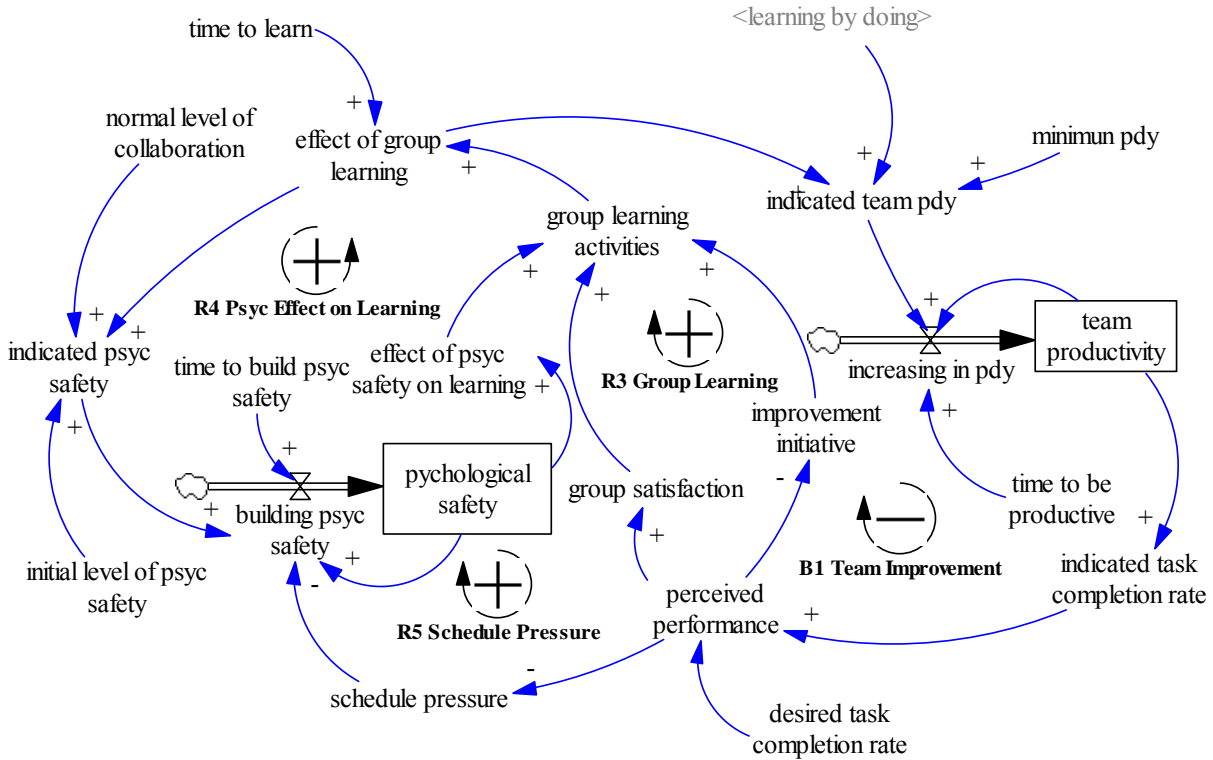


Figure 7: Psychological safety and group learning sector

We make appropriate changes to Lizeo's work (2005) to come up with the tentative sub model shown in figure 7. The basic idea of this sub-model follows the feedback structure of socio-psychological factors in CPD. In the left side we formulate *psychological safety* as a stock that accumulates as more group process improvement is achieved. Two organizational context related factors, *normal level of collaboration* and *initial level of psychological safety* affect psychological safety as well. In the right side we model team productivity as a stock and it affects *indicated task completion rate* directly. The two stocks both go into a reinforcing loop Group Learning (R3) in the middle and enable *group learning activities*. These learning activities stimulate the *effect of group learning* in the upper-middle and the learning effect further revives the team productivity loop (B1) and the psychological safety loop (R4).

It is not easy to carry this particular sector further through empirical validation since we may not be able to get primary data to calibrate each parameter in the model. Nonetheless, by interviewing engineers and project managers, we are able to form a reasonable estimation of constants and variables in the model so that we measure the psychological and social construct in an adequate manner. We also seek for theoretical support (Edmonson, 2004; Kozlowski and Ilgen, 2006; Carmeli et al. 2009) for us to finish model formulation and make sure that this sub-model has expert/content validity. Model validation is essential for us to build confidence in using the model later on. Only after calibrating and validating the model, can we move on to conduct simulation experiments and policy design (Oliva, 2003).

4. Simulation Analysis

In this section we begin from adjusting the normal level of manufacturer-supplier collaboration and the initial level of psychological safety. Three levels (0.5, 0.7, and 1.0) are tested. Figure 8 and Figure 9 illustrate the change in team productivity, psychological safety, and group learning activities in both cases.

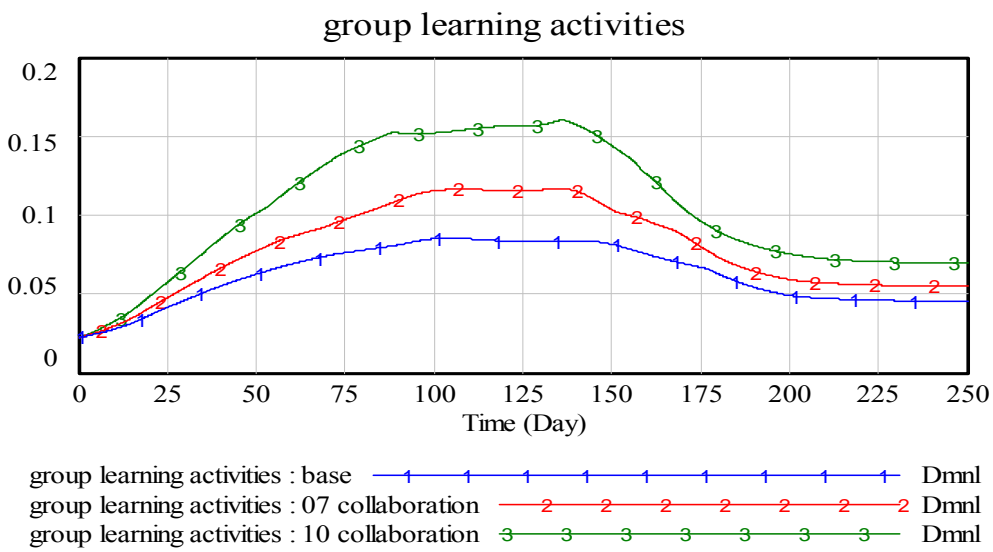
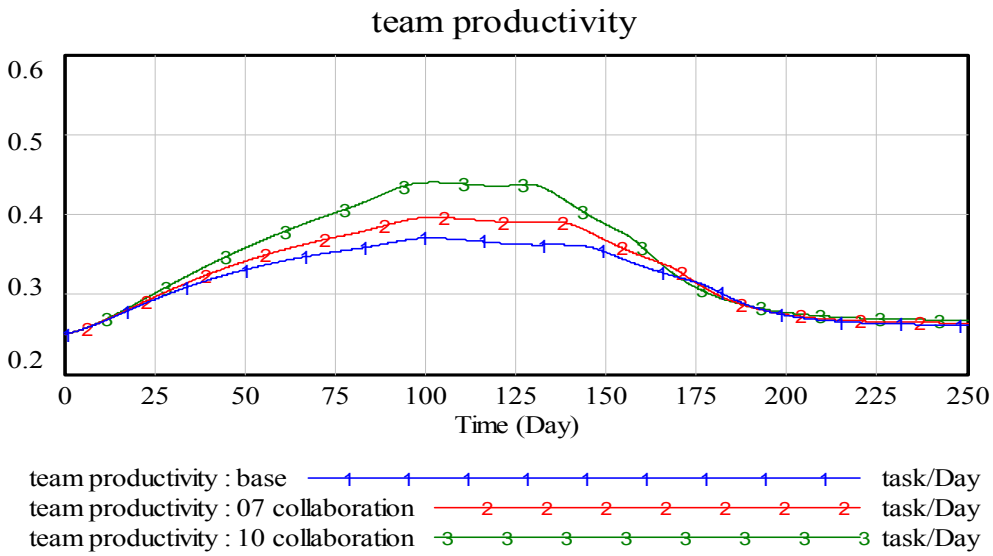
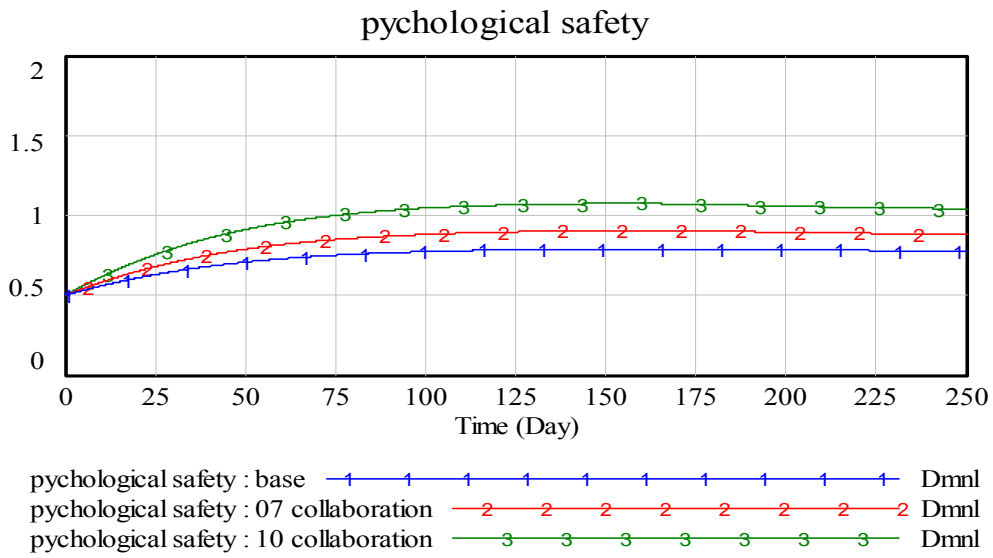


Figure 8: Performance change under different initial levels of collaboration

Figure 8 illustrates the change of team performance under different levels of collaboration. In general higher manufacturer-supplier level of collaboration leads to better performance. The return of productivity improvement seems to be constant and no surprising behaviors show up. On the other hand, when we adjust the initial level of psychological safety, we find some interesting behaviors. First, as the top of figure 9 illustrates, the CPD team with highest initial level of psychological safety (1.0) reveals a two-stage growth mode. This mode explains why group learning activities rise up again at 125th day as the second stage of growth begins. Second, as the bottom of figure 9 illustrates, the highest level of psychological safety does not foster the most group learning activities all the time. A possible explanation is that the team improvement (B1) loop dominates in a certain period in which *improvement initiative* (see figure 5) decreases and group learning declines.

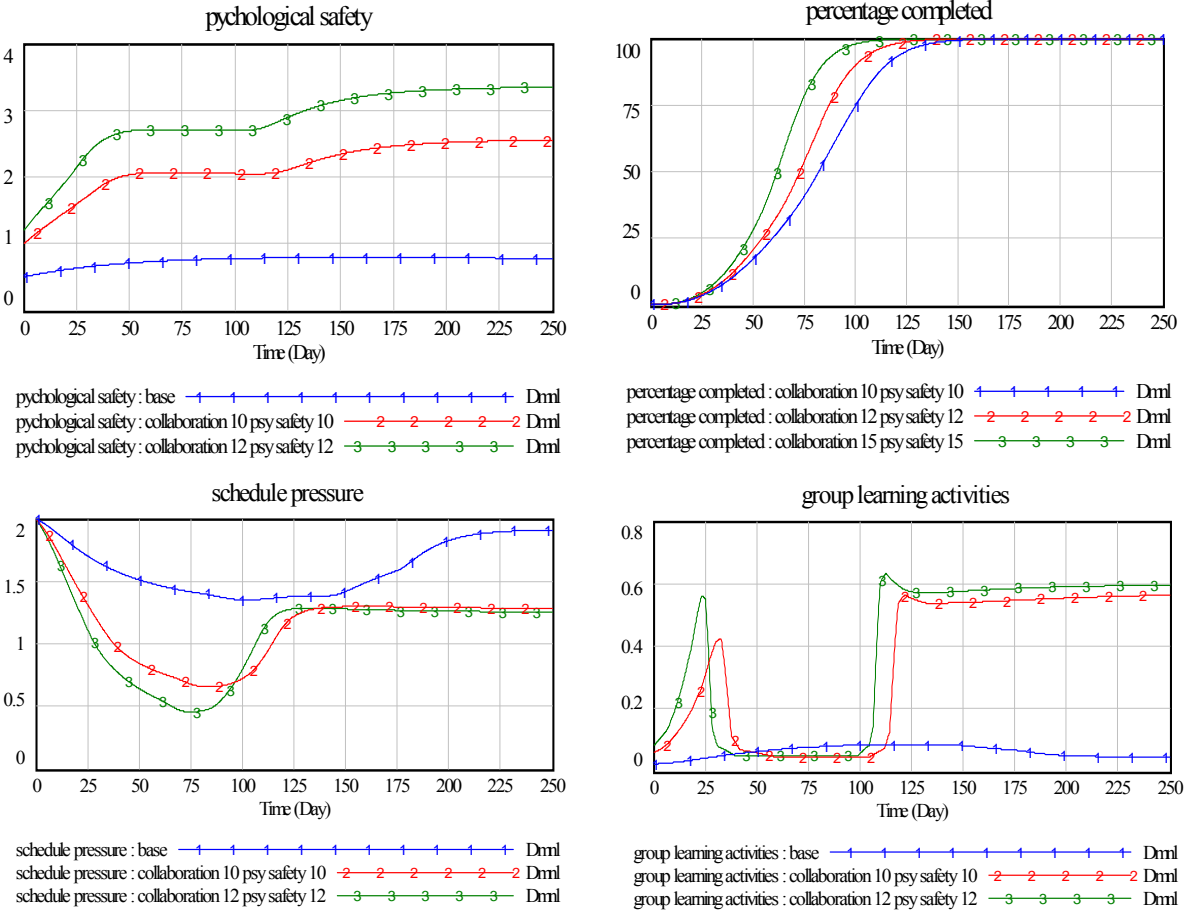


Figure 10: Performance change under different initial levels of both factors

Figure 10 illustrates the potential influence of adjusting the values of level of psychological safety and level of collaboration simultaneously. Again we observe a two-stage growth mode of psychological safety, which has been found in the previous literature. The double growth reflects that the CPD team has a second drive to improve in the latter stage such as process development and keeps group learning at a high level. Not surprisingly, higher levels of collaboration and psychological safety reduce schedule pressure and help the team finish tasks in a shortest cycle-time. However, they do not foster the most group learning activities all the time.

In the last part of the simulation analysis, we assume that the companies ignore enhancing normal level of psychological safety and manufacturer-supplier collaboration (both levels are set as 0.5), and merely set up higher performance goals (finishing tasks/day). Under such circumstances, three different performance goals (0.5, 0.7, and 1.0) are tested.

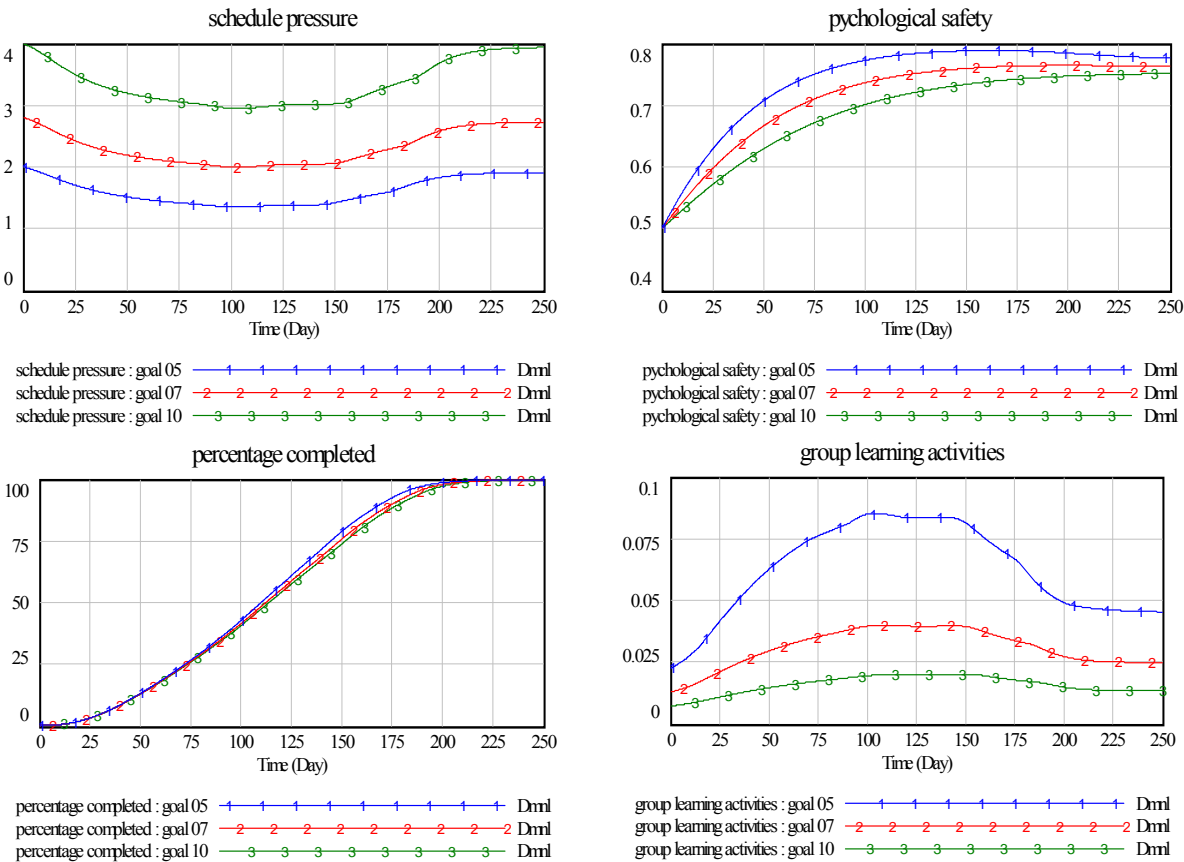


Figure 11: Performance change under different initial levels of performance goal

Figure 11 exhibits the results of our mental experiments. Without considering the level of psychological safety and the level of collaboration, team performance deteriorates significantly. Even psychological safety grows slowly as the progress advances, group learning activities are comparatively few. The CPD team then fails to make cycle-time reduction happen (see percentage completed). Based on the simulation results, we provide following three propositions:

Proposition I: The managerial board of CPD teams should explicitly encourage increasing *frequency of communication* and *amount of review* (Burchill and Fine, 1997). Team leaders are supposed to praise the shared problem solving and caring behavior (Bstieler and Hemmert, 2009). These countermeasures motivate and achieve higher level of manufacturer-supplier collaboration and higher initial level of psychological safety. Both factors are high leverage points to help CPD teams to attain cycle-time reduction.

Proposition II: In CPD processes, the manufacturer and the supplier have to create a safe, supportive, encouraging and engaging environment to foster productive vertical development partnerships. Yet, the highest level of psychological safety does not lead to most group learning activities all the time because the improvement initiative decreases. Leadership skills may be the key to stimulate group learning as well.

Proposition III: Manufacturers should avoid free lunch thinking when they try to deploy collaboration software. The manufacturer cannot just implement CPD, set up higher performance goals, and achieve operational success without building up collaborative competence with the supplier (Mishra and Shah, 2009) or providing a working environment where team members easily establish psychological safety. Without doing so, the higher performance goal in turn harms group learning, team productivity, and time efficiency.

5. Discussion

The contribution of this study is two-fold. First we present a SD inquiry to help the inter-organizational project team understand how cognitive and social factors such as psychological safety and group learning, rather than technical factors such as the deployment of collaboration software, affect the duration of CPD projects. We link organizational studies and behavioral operations to improve operational performance and enhance group learning. More importantly, the two-stage growth mode of psychological safety in CPD processes should be an interesting starting point of developing a dynamic theory.

Second, existing SD models on project management or have investigated schedule pressure, fatigue, rework, change management, resource allocation, fire-fighting, tipping point dynamics, trust, knowledge sharing, etc (Lyneis and Ford, 2007). Our model addresses psychological safety, a construct that has not been addressed by other SD studies on analyzing project dynamics. After we identify dominant feedback loops, we set up a simulation model integrating empirical workflow and theoretical constructs to articulate the complexities of CPD. By doing so, we bring a whole new application of SD modeling to the SD community.

Research applying innovative methods on product development and learning in project teams is promising (Edmonson and Nembhard, 2009). The SD simulation we use by its nature fits with investigating behavioral operations. We design simulation experiments to help managers find high leverage points to reduce development cycle-time. For instance, by testing different initial levels of psychological safety and the normal level of collaboration, we see the potential influence of behavioral factors on time efficiency. The simulation analysis is of pragmatic value because knowing the importance of creating a safe climate and collaborating, the manufacturer and the supplier may try to consolidate vertical development partnerships. Based on simulation results we generate three propositions serving as the basis of developing a dynamic theory of psychological safety and group learning in CPD projects.

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Appendix A: CPD workflow sub-model equation

Equation (1) shows that *CPD tasks to do (manufacturer)* (T_{CPDm}) is depleted by *working rate (manufacturer)* (W_m). Equation (2) determines W_m , which is the minimum value between *indicated task completion rate* (IW_m) and process limit. Process limit is a rate defined as tasks available for manufacturer ($T_{CPDm} * PC_m$) over *task process duration* (λ_m). PC_m represents *process concurrency (manufacturer)*, which is a function of *percentage completed* (η). Equation (3) is a lookup function in which process concurrency increases nonlinearly as the percentage completed becomes higher (Ford and Sterman, 1998).

$$(1) \quad (d/dt)(T_{CPDm}) = -W_m$$

$$(2) \quad W_m = \text{Min} (IW_m, T_{CPDm} * PC_m / \lambda_m)$$

$$(3) \quad PC_m = f(\eta)$$

Equation (4) confers that defected tasks after initial completion enter *unknown defective tasks to co-review (manufacturer)* stock (T_{UDREVm}). The net flow is the difference between inflow, W_m multiplying *fraction of rework* (ϵ) and outflow, *recognizing problems rate* (R_m). Equation (5) defines R_m as T_{UDREVm} over *co-review duration* (τ), a function of *psychological safety* (Θ). In equation 6 τ decreases nonlinearly as Θ accumulates.

$$(4) \quad (d/dt)(T_{UDREVm}) = W_m * \epsilon - R_m$$

$$(5) \quad R_m = T_{UDREVm} / \tau$$

$$(6) \quad \tau = f(\Theta)$$

Equation (7) calculates the net flow of *tasks to re-do* stock (T_{REm}). The net flow is the difference between R_m and *problem solving rate (manufacturer)* (P_m). The way we define P_m in equation (8) is similar to equation (2). Equation (9) shows that the sum of *aggregate working rate* (AW), P_m , and *problem solving rate (supplier)* (P_s) minus releasing rate (L) equals to the net flow of *non-defective tasks to co-review* stock.

$$(7) \quad (d/dt)(T_{REm}) = R_m - P_m$$

$$(8) \quad P_m = \text{Min} (IW_m, T_{REm}/\mu_m)$$

$$(9) \quad (d/dt)T_{NDREV} = AW + P_m + P_s - L$$

Equation (10) computes *non-defective aggregate working rate* (AW), which is the sum of non-defective W_m and non-defective *working rate (supplier)* (W_s). Equation (10) shows the *fraction of rework* (ϵ). This fraction, similar to PC_m (see equation (3)), is a function of *percentage completed* (η) and decreases as η increases. Equation (12) simply shows that *tasks completed stock* (T_{comp}) accumulates as finished tasks pass through co-review stage and flow into T_{comp} through *releasing rate* (L).

$$(10) \quad AW = (W_m + W_s) * (1 - \epsilon)$$

$$(11) \quad \epsilon = f(\eta)$$

$$(12) \quad (d/dt)(T_{comp}) = L$$

Equation (13) computes η , the percentage completed of a CPD project. T_{comp} is divided by *total tasks to do* (T_{total}), which is sometimes called project backlogs. The percentage is further used as input to three nonlinear functions so that we can get ϵ , PC_m , and *process concurrency (supplier)* (PC_s). The way we set PC_s is similar to equation (3). Equation (14) shows that *psychological safety* (Θ) accumulates as *building psychological safety* (b) flows into the stock. Equation (15) confers that *indicated task completion rate* (IW_m) is equaled to *team productivity* (Ψ). Equation (14) and (15) are formulated in psychological safety and group learning sector of the SD model.

$$(13) \quad \eta = (T_{comp}/T_{total}) * 100$$

$$(14) \quad (d/dt)\Theta = b$$

$$(15) \quad IW_m = \Psi$$

Above-listed equations cover the manufacturer's flow in the upside of workflow sector (see figure 6). With minor changes in parameters' setting, the equations can be applied to the supplier's flow in the downside of CPD workflow sector as well.