OPTIMIZING A DESIGN CHAIN IN THE COLLABORATIVE DESIGN ENVIRONMENT BY INTEGRATING PLC INTO SSDM

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Abstract: The importance of collaborative design (CD) to the competitiveness of enterprises has been frequently emphasized. Since CD is highly related to the product development process that involves internal and external organizations, such an environment of a design chain is usually rather complex. Within such a complicated process, soft systems dynamics methodology (SSDM), which consists of soft systems methodology (SSM) and systems dynamics (SD), can be applied to improve the design chain. Product life-cycle cost (PLC) is shown to be an effective measurement to evaluate the performance of a product design process. However, previous literature on SSDM has not been integrated with PLC concept. This study proposes a methodology based on SSDM that evaluates the total cost across different stages of product design in order to optimize a design chain in the CD environment. By integrating PLC into SSDM, the proposed methodology evaluates associated product design activities and minimizes the total costs in order to optimize a design chain.

INTRODUCTION

In confront with the global competitive and fast changing markets, companies today outsource gradually and concentrate more on their core competency in order to increase their profitability. This leads firms not only to optimize their interior product development processes, but also to strengthen their exterior relationships with key suppliers and customers (Wang and Lin 2006, Lyu and Chang 2007). With early involvement of key suppliers and customers in the product development process, the engineering changes of a product, time to make a product and costs incurred in the design chain (DC) can be reduced. However, the understanding of customers' needs in the early product development process is usually imprecise, and costs are hard to be estimated. Thus, how enterprises resolve these questions has become a great concern (Xu et al. 2006).

Product life-cycle cost (PLC) is one of the measurements to evaluate the performance of a product lifecycle. This measurement evaluates total cost incurred in a product lifecycle and assists managers or engineers in making decisions in all phases of a product design process, in which some decisions and tradeoff exist (Hatch and Badinelli 1999). These decisions and tradeoff may result in a much more complex product development environment.

In the collaborative design (CD) environment, it is necessary for firms to have an effective mechanism to manage the DC. However, it lacks an explicit systematic approach to encourage enterprises to measure the performance of a collaborative product development process, resulting in organizations not well managing processes associated with the product design, let alone improving the process.

A typical problem of a product design process can be viewed as a network. If a company reengineers its business process, decision makers will determine how much money to invest on the process and consider how long to produce a product in a reduced time. According to Krishnan and Bhattacharya (2002) and Hillier and Lieberman (2005), the technology selection, which means the design flexibility, shortens the duration of a design process while increases the total cost. A PLC model can be applied to trade the time and cost off.

This study adopts the soft systems dynamics methodology (SSDM) by Paucar-Caceres and Rodriguez-Ulloa (2007) to identify problems in a product design process. SSDM consists of Soft systems methodology (SSM) and Systems dynamics (SD). However, SD cannot analyze complex problems, especially in the product design process. As a result, a PLC model is integrated into SSDM in this research to improve the needed-to-be-improved product development process in order to minimize the total cost and to reengineer the process.

LITERATURE REVIEW

Research on Collaborative Design and Product Lifecycle Management

Confronting with the modern competitive environment, firms integrate cross-functional teams and supply chain members to execute important product development processes and to share responsibility, quality and accountability in order to achieve competitive advantages (Noori and Lee 2004). Therefore, when various designers co-design a product, the process is called collaborative design (CD) (Wang et al. 2002).

Some previous researches showed that enterprises could gain benefits by applying CD to their product design processes. Littler et al. (1995) identified that when firms cooperatively involved in the product development process, time to make products could be reduced. Wang, et al. (2002) indicated companies shared risks and costs through collaborating with partners. McIvor and Humphreys (2004) also pointed out that organizations early aligned with suppliers could exchange information mutually.

As distinct department works together and highly interacts one another in the CD environment and enterprises work together with different goals, the CD environment regarding the product design will be much more complicated (Gerwin and Barrowman 2002). Wang, et al. (2002) indicated that firms could apply Web to share data, information and knowledge, and to monitor the design process and check the statuses of the working system. This assists managers and engineers in making decisions immediately and, hence, reduces the communication time and changeable costs.

Information changes in a product management system were updated by engineers at server ends, but these systems were often restricted to some specific product lifecycles. A new management system, called product lifecycle management (PLM), was developed. PLM is a strategic and information-oriented method to integrate different people, processes, practices and technologies into a product lifecycle, which comprises the product design, production, customer use, support and disposal (Asiedu and Gu 1998, Sharma 2005), Githens 2007, Jun et al. 2007, Kopacsi et al. 2007).

PLM helps a corporation and its extended enterprise construct the backbone for product information. It consists of foundation technology and standards (e.g., XML, visualization and enterprise application integration), analysis tools (e.g., FEA, CAD and MDA), core functions (e.g., data files, file management, workflow and project management) and functional applications (e.g., product configuration management) (CIMdata: http://www.cimdata.com). Sudarsan et al. (2005) established a framework of PLM, which included IT infrastructure, product information modeling architecture, development toolkit and some business applications. IT infrastructure comprises basic PLM functions, such as software, hardware, network and so on.

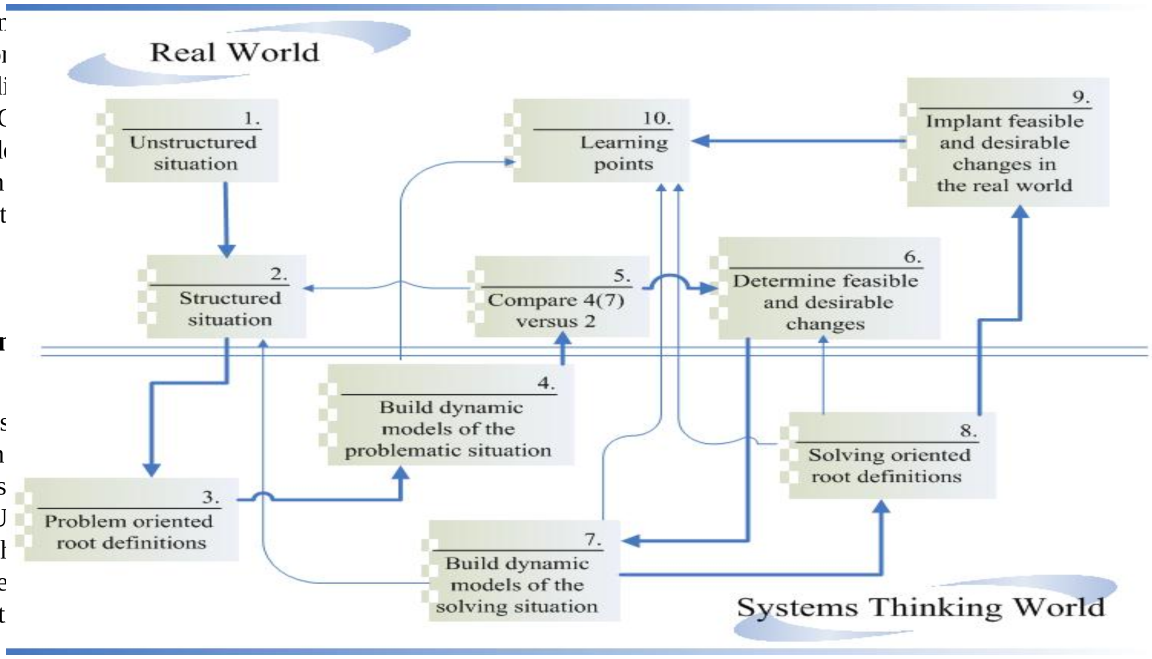
Research on Product Life-cycle Cost

The concept of product life-cycle cost (PLC) originates from the US Department of Defense. The military PLC has a rigid time frame and confined groups. However, it lacks a commercial style accounting system and is limited to only procurement purposes (Asiedu and Gu 1998, Hatch and Badinelli 1999, Xu, et al. 2006). PLC is one of the PLM measurements to trace and analyze accounting information incurred in every product development stage, while containing costs and environmental burdens (Ebeling 1997, Prasad 1999, Xu, et al. 2006).

Speaking of PLC, life cycle assessment (LCA) is also an important issue. LCA provides some information pertaining to the environmental effects caused by products and processes. Zhang et al. (1999) considered PLC and LCA to construct the green quality function deployment-II (GQFD-II) for product developments and improvements. For the automobile industry, Mildenberger and Khare (2000) delineated how to make an environment-friendly car when manufacturers took environmental effects and existing cost-analyzing tools into consideration.

Dowlatshahi (2001) proposed three levels (strategic, operational and tactical) of PLC. At the strategic level, organizations are required to consider costs and strategies associated with the product design. At the operational level, enterprises should think over whether total throughput costs meet the strategies from different organizations to make a rational price of a product. At the tactical level, buyers, distributors and in-house workers need to put costs of purchased materials and delivery times into account. Besides, Asiedu and Gu (1998) also described that the company cost, users cost and society cost should be considered in PLC contents.

According to Asiedu and Gu (1998) and Xu, et al. (2006), cost estimating models could be divided into parametric models, analogous models and detailed models. Prasad (1999) delivered a model for optimizing the product performance by considering reliability, PLC and other measurements (such as unscheduled changes, time to market, costs of quality and so on). Hatch and Badinelli (1999) developed a methodology, which combined dynamic programming, to carry out the design tradeoff in every lifecycle stage based on PLC and availability of a product. Furthermore, fixed asset depreciation, the preventive maintenance and minimal repair were put into a model proposed by Monga and Zuo (2001) to estimate the preventive maintenance on the product's or system's hazard rate ar ... tal cost and to encourage coı ... Accordi ... ıis study. The proposed PLC ... C model is for the product de ... performance of this design ... nances cannot be utilized int



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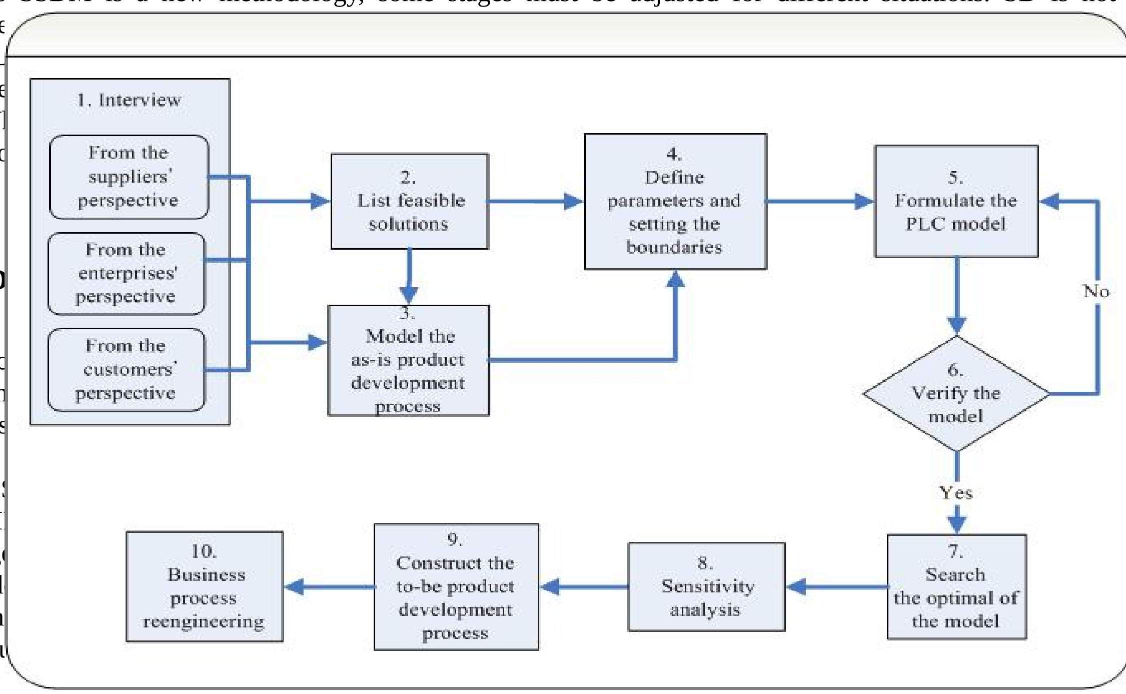
Source: Rodriguez-Ulloa and Paucar-Caceres 2005

Fig. 1. The general view of SSDM.

This study focuses on the optimization of product design rather than a specific behavior to be simulated or tested. Hence, SD should be modified for this study. Instead of SD, this study integrating PLC into SSDM has following reasons.

1. As SSDM is a new methodology, some stages must be adjusted for different situations. SD is not an appropriate me...
2. PL ... ed SSDM can ide ... ess.
3. Wl ... ed by the PLC mo...



PROPOSED

The prac ... hes associated with optimizin ... be the product design process ... o depict some activities and ... form a new methodology, ...

SSDM-I ... LC to develop a new ten stag ... ms existing in the product d ... f the problem situation-orien ... embedded into the solving situ ... are as below.

Fig. 2. The general view of SSDM-II.

Real World

It is intricate and unstructured in the real world. The main purpose of stage 1 and stage 2 is to capture problems and overall conditions in the collaborative product development process. As suppliers and customers involve in the early collaborative product development process, the DC members are expected to know the lifecycle of the DC in order to explore problems. Detailed descriptions are as below.

1. Stage 1: interview with the enterprise and its suppliers and customers

    The first thing is to form a project team. After interviewing with the enterprise and its key suppliers and customers, this project team could know some points, such as time to market, product costs and design quality. Some problems, which the DC members confront with, can be also included in this stage in order for further parameters definitions.

    Rich picture can be used in this stage to discover overall events, problems, processes and the interactions among these processes. After considering all the perspectives from an enterprise and its key suppliers and customers, the project team models the as-is product development process.

2. Stage 2: list feasible solutions

    From interviewing with the DC members, the project team defines different stages and records some feasible solutions. Rich picture can be also utilized to define the scope of the problem.

Problem-Situation Systems Thinking World

In the problem-situation systems thinking world, the as-is model is to describe the problems associated with the product design. This model is also helpful for new parameters definitions and boundary settings. The main purpose of stage 3 and stage 4 is to transfer the information and current product development process of the real world into the languages of the problem-situation systems thinking world.

3. Stage 3: model the as-is product development process

    Based on the interview and rich picture, the project team exploits CATWOE analysis to define the scope of the current product development process (Presley et al. 2000). After defining CATWOE, this team will model the as-is product development process. Moreover, when modeling the process, this team should also put the interactions among the DC members into consideration.

4. Stage 4: define parameters and set their boundaries

    This project team refers to the rich picture, the as-is model and CATWOE analysis (refer to stage 1 to stage 3) to define decision variables and parameters. Decision variables are values to be determined while parameters are the coefficients or right-hand sides of the objective function and subject constraints (Hillier and Lieberman 2005). The boundaries and parameter values will be obtained from the interview or some available data. Following are the decision variables and parameters.

Decision variables:

x_i reduction in the duration of stage i due to the CD effect, for $i = 1, 2, 3, ..., N$;

y_j start time of stage j (for $j = 2, 3, ..., N$), given the values of $x_1, x_2, ..., x_N$;

Y_{fin} the finish node of a project.

Parameters:

c_i marginal cost for each stage i due to the CD effect, for $i = 1, 2, 3, ..., N$;

D the number of testing samples;

p the average yield rate for a product;

o_i the original duration time of each stage i, for $i = 1, 2, 3, ..., N$;

r_i the maximum reduction in time;

T_d due date of the project.

Solving-Situation Systems Thinking World

Traditional SSDM in the solving-situation systems thinking world uses SD to formulate a model in order to search an optimal solution to a specific problem existing in the real world. However, SD cannot analyze complex problem; it is not an appropriate methodology for this study. This research conducts a mathematical model to formulate a needed-to-be-improved product design process. Hatch and Badinelli (1999) indicated that a concurrent optimization model could help a company to make decisions over different stages of a product development process. This study takes the marginal cost analysis as a viewpoint to improve a faulty product development process. Detailed descriptions of stages 5, 6, 7 and 8 are listed below.

5. Stage 5: formulate the PLC model

    This DC optimization problem is a network model for optimizing a project's time-cost tradeoff. The way of solving this problem is the marginal cost analysis. Each activity can be viewed as one stage. Different cases will result in distinct sequential and parallel routes.

Krishnan and Bhattacharya (2002) defined the technology selection as the design flexibility which has great impact on the performances of a new product development. Specifically, this design flexibility affects the duration and total cost of a product development process. This study utilizes the concept of Krishnan and Bhattacharya (2002) to determine the design flexibility as the construction of a collaborative platform, which has influences on the duration and cost of each activity. The objective function is the linear programming model given below.

$$Min = \sum_{i=1}^{N} c_i * x_i \quad \text{for } i = 1, 2, 3, ..., N \tag{1}$$

This objective function is subject to the following constraints. The maximum reduction constraint due to the collaborative platform effect is as follows.

$$x_i <= r_i \quad \text{for } i = 1, 2, 3, ..., N \tag{2}$$

The start time of each stage is related to the start time and duration of each of its immediate predecessors. The duration is defined as the normal time of each stage minus the reduction time owing to the collaborative platform effect. The duration constraint is as below.

$$y_j >= y_{j-1} + (o_i - x_i)$$

$$\text{for } i = 1, 2, 3, ..., N$$

$$j = 2, 3, ...N \tag{3}$$

$$y_{fin} <= T_d \tag{4}$$

Decision variables should have non-negativity constraints. These variables include the finish node, start time and reduction time of each stage.

$$y_{fin} >= 0 \tag{5}$$

$$y_j >= 0 , \quad x_i >= 0 \tag{6}$$

6. Stage 6: verify the model

The company and its suppliers and customers will verify that the PLC model actually captures the problem of the needed-to-be-improved process. If this model does capture the problem of the real product development process, go to stage 7; otherwise, return to stage 5 to reformulate the model.

7. Stage 7: search the optimal of the model

Once the PLC model is verified, the project team estimates parameters' values by collecting available data and conducting extensive interviews with senior managers and engineers. This team then applies LINGO 8.0 software to search the optimal of the model. It should be noticed that this result is the minimum marginal cost. The sensitivity analysis is also applied to find out the needed-to-be-improved processes.

8. Stage 8: sensitivity analysis

In this stage, it is very important to test the model after the initial optimal solution is determined. Sensitivity analysis, which determines the parameters whose values cannot be changed without changing the optimal solution, is one of the post-optimality analyses to test the model. Following are the reasons to test the model (Hillier and Lieberman 2005).

I. The optimal solution may not be optimal. That is, the optimal solution for the original model may be much different from ideal for the real problem of the product development process.

II. Sensitivity analysis addresses problems regarding what would occur to the optimal solution when changes are made to the model.

III. Sensitivity analysis determines which parameters are sensitive or insensitive to the optimal solution.

Real World

Once the current product development process problem has been solved by PLC model, the solution will be the reference for the to-be product development process. Senior managers in a company will refer to this to-be process and then reengineer the faulty product development process. Detailed descriptions about the construction of the to-be product development process (stage 9) and the business process reengineering (stage 10) are listed below.

9. Stage 9: construct the to-be product development process

The enterprise and its suppliers and customers have extensive communications with each other for improving the current product development process. Because customers are familiar with market trends and suppliers are acquainted with skills, the DC members do share knowledge and expertise mutually. Through collaboration, the project team constructs the to-be product development process.

10. Stage 10: business process reengineering

Before conducting the business process reengineering, the project team should refer to CATWOE analysis and draft a schedule using Gantt chart. This chart not only illustrates the start and finish dates of the terminal elements but also provides the checklists of a project. As Table 1 shows, the ten stages of SSDM-II are summarized.

Table 1. Briefing of the ten stages of SSDM-II.

Stages	Description and Objective	Outputs
1. Interview with the enterprise and its suppliers and customers 2. List feasible solutions	1. Establish a project team to execute the business process reengineering. 2. Rich picture is utilized to define the scope of the problem as well as issues the DC members have concerns with.	Project team Rich picture Corresponding strategies Stage definitions
3. Model the as-is product development process 4. Define parameters and set their boundaries	1. Exploit CATWOE analysis to define the scope of the as-is product development process. 2. The decision variables and parameters are defined for the PLC model.	CATWOE analysis As-is process Decision variables Parameters
5. Formulate the PLC model 6. Verify the model 7. Search the optimal of the model 8. Sensitivity analysis	1. Take the cost minimization aspect to improve a faulty process. 2. Apply LINGO 8.0 software to search the minimum marginal cost. 3. Find out the needed-to-be-improved activities using sensitivity analysis.	PLC model Optimal solution Sensitivity analysis
9. Construct the to-be product development process 10. Business process reengineering	1. DC members discuss with each other to construct the to-be product development process. 2. Once the to-be process is adopted by senior manager, the project team drafts a schedule using Garnet chart.	To-be process Gantt chart

AN ILLUSTRATIVE EXAMPLE

In this section, the study uses a simple example to illustrate the proposed model built in section 3. This example provides users with a complete overview on how these ten stages work.

Real world

Due to the growing popularization of the broadband network, the digital entertainment device will be integrated into the personal computer in the near future. The case company X, which is a computer manufacturer, is creating such innovative computer products. The main customer of the company X is the company C while the main suppliers include the hardware vendor (Vendor H), the software vendor (Vendor S) and the mechanical vendor (Vendor M). In order to motivate the process reengineering, the case company forms a project team, named Team X, and the vice general manager is the project leader. Team X is composed of the company X's interior departments (the research and development department (R&D) and the manufacturing sector) and its exterior organizations (the company C and venders H, M and S).

1. Stage 1: interview with the enterprise and its suppliers and customers
2. Stage 2: list feasible solutions

Team X records problems and corresponding strategies from the company X, Venders H, M and S and the company C by rich picture. The problems are summarized as follows.

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Problem-Situation Sys

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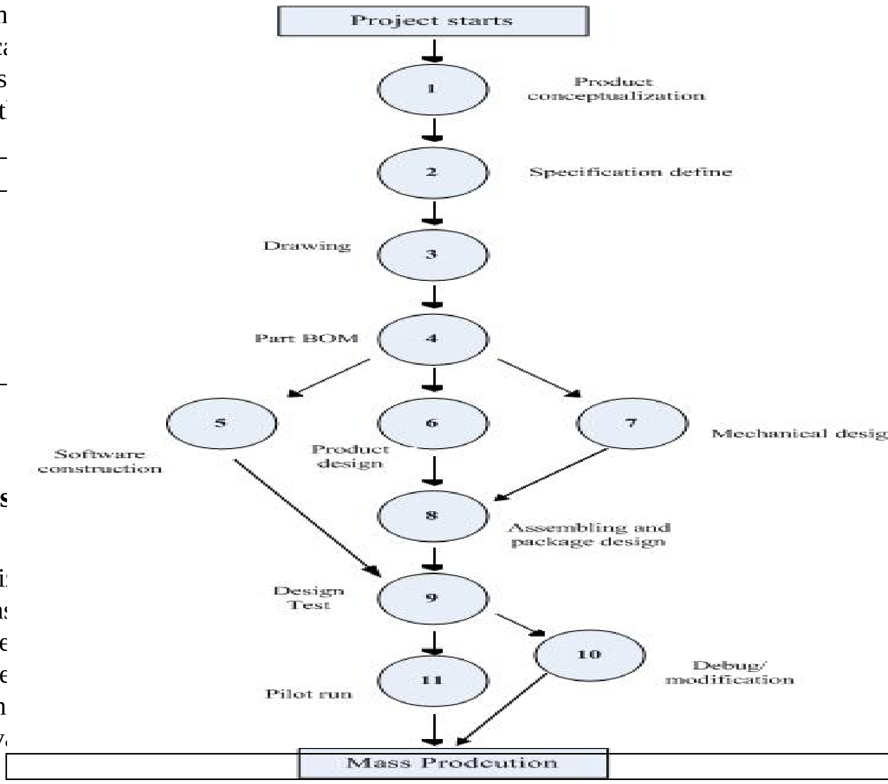

Fig. 3. The as-is model.

Solving-Situation Systems Thinking World

Team X formulates a PLC model to solve the problem in the real world. Following are the explanations of stages 5, 6, 7 and 8.

5. Stage 5: formulate the PLC model

Based on the as-is process, the rich picture and the CATWOE analysis, Team X builds the time-cost tradeoff table by using historical data and interviews in Table 3.

As Table 3 states, The “Stage” column represents the eleven stages of the as-is process model. The “Normal Time” column indicates the original time that each stage spends while the “Reduced Time” column depicts the reduced time due to the construction of the collaborative platform. The “Normal Cost” column demonstrates the original cost that each stage costs whilst the “Increased Cost” column points out the increased cost due to the construction of the collaborative platform. Note that the platform construction causes the reduced time, but it leads to the increased cost. The “Maximum Reduction in Time” column is the differences between the “Normal Time” column and the “Reduced Time” column. Besides, the “Increased Cost” column minus the “Normal Cost” column leaves the “Reduced Cost per Day Saved” column.

6. Stage 6: verify the model

Team X interviews with venders H, M and S, the company X and the company C many times. The PLC model is formulated based on the as-is process; the DC members agree that this PLC model actually describes the as-is process. Team X then goes on to stage 7.

Table 3. Time-cost tradeoff data for the stages of the project.

Stage	Time		Cost		Maximum Reduction in Time (Days)	Reduced Cost per Day Saved
	Normal Time (Days)	Reduced Time (Days)	Normal Cost ($ per Day)	Increased Cost ($ per Day)		
1	10	8	10,000	10,100	2	100
2	2	0.5	10,000	10,100	1.5	100
3	5	4	10,000	10,100	1	100

4	3	2	10,000	10,100	1	100
5	25	20	10,000	10,100	5	100
6	20	16	10,000	10,100	4	100
7	20	15	10,000	10,100	5	100
8	5	4.5	10,000	10,100	0.5	100
9	10	7	10,000	10,100	3	100
10	16	12	10,000	10,100	4	100
11	10	8	10,000	10,100	2	100

7. Stage 7: search the optimal of the model

Team X uses LINGO 8.0 to search the optimal of the model. The results are as follows.

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Real World

Team X i

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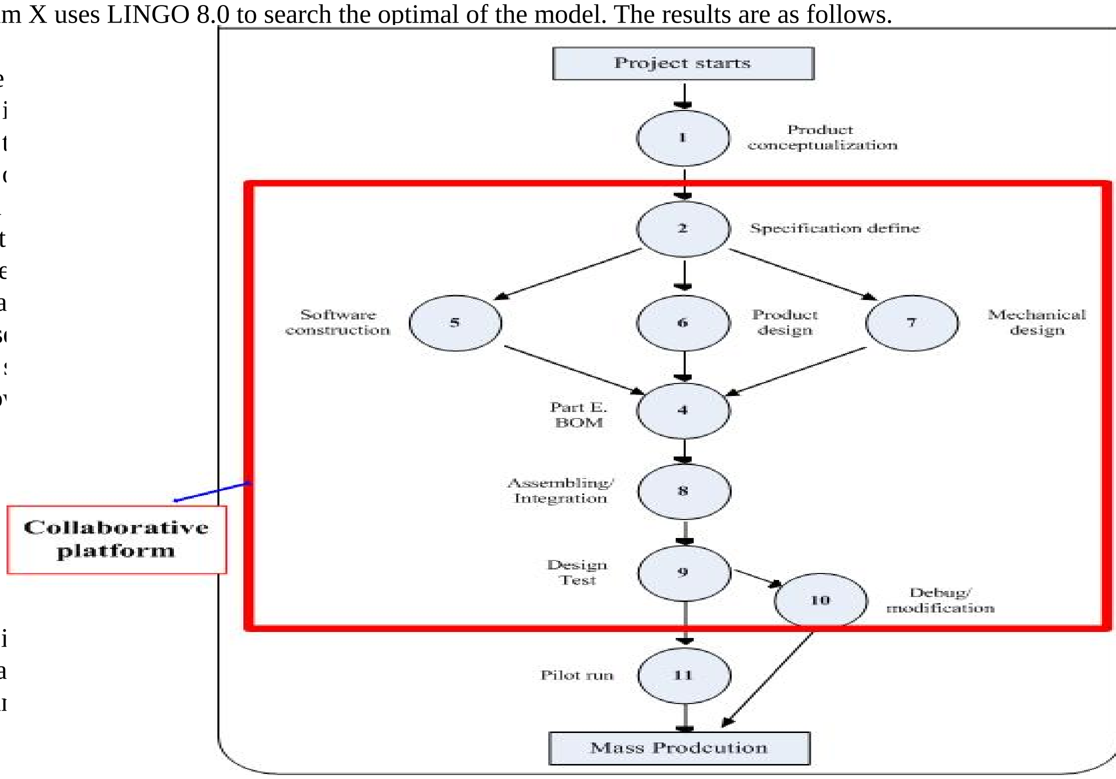

Fig. 4. The to-be product development process.

Due to the construction of the collaborative platform, the durations of some activities can be greatly reduced. Once the product is conceptualized, venders S, H and M, the companies X and C and Team X discuss together and define the product specification, whose information is then uploaded onto the database of the collaborative platform. Different venders will be informed and then make products. The platform makes the auto BOM and the prototype would be tested afterwards. The last step is the pilot run. Once pilot run is done, these products are put into the mass production.

From this extensive interview, the company X focuses on the cost, time to market and quality. Through the collaborative platform construction, time to make products can be reduced, the cost to construct the platform is less than the budget and the quality of the products can also be enhanced since the engineering changes are reduced. Total time of this process:

$8+1+24+(1/24)+5+10+12=60.041$ (days)

Cost increased:

$$100*(10-8)+100*(2-1)+100*(25-24)+100*(20-19)+100*(20-19)+100*(16-12)*(1-0.98)*100=1400 \quad \text{(dollars)}$$

Total cost of this process: $1,260,000+1400=1,261,400$ (dollars)

Time reduced: $(71-60.041)/71=15.44\%$

Cost increased: $1400/1,260,000=0.11\%$

10. Stage 10: business process reengineering

After this to-be process is checked by senior managers, Team X then drafts the schedule using Gantt chart for the business process reengineering.

CONCLUSIONS

In confront with the globalized and competitive markets, enterprises are expected to integrate with their suppliers and customers in order to strengthen their research and development capabilities and to make customer-satisfied products. However, companies nowadays lack a systematic approach to analyze their product development processes in order to optimize their DC in the CD environment. As a result, this study applies SSDM to help enterprises justify such a deficiency. The contributions of this research are as follows.

a. SSM has the advantages of analyzing complex problems in the real world and providing some feasible solutions. SSDM consists of SSM and SD. Thus, based on SSDM, SSDM-II can identify a company's problems in its product development process and list some feasible solutions by interviewing with DC members.
b. PLC can be applied to trace and analyze accounting information incurred in every product development stage (Xu, et al. 2006). In this study each design activity is defined as one stage. For meeting the deadline by spending more money to expedite some activities with respect to the product design, a PLC model is formulated to optimize the time-cost tradeoff.
c. The PLC model only provides the minimum total cost of a design's process. The sensitivity analysis is exploited to assist a company in uncovering the most needed-to-be-improved activities. The DC members will tune up some design activities by referring to the optimal and sensitivity analysis in order to construct the to-be product development process.

In order to justify the effectiveness of this approach, this study applies an illustrative example. After the project team analyzes the project by using PLC model, the case company only invests 1,400 to shorten the lifecycle from 71 days to 60 days and delivers an optimal to-be product development process.

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