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A Business Process Intelligence System for Enterprise Process Performance Management

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Abstract

Business process management systems traditionally focused on supporting the modeling and automation of business processes, with the objective of enabling fast and cost-effective process execution. As more and more processes become automated, customers are increasingly interested in managing process execution. This paper presents a set of concepts and a methodology towards business process intelligence using dynamic process performance evaluation, including measurement models based on ABM (Activity Based Management) and a dynamic enterprise process performance evaluation methodology. The proposed measurement models support the analysis of six process flows within a manufacturing enterprise including activity flow, information flow, resource flow, cost flow, cash flow, and profit flow, which are crucial for enterprise managers to control the process execution quality and detect problems and areas for improvements. The proposed process performance evaluation methodology uses *time, quality, service, cost, speed, efficiency*, and *importance* as seven evaluation criteria. A prototype system supporting dynamic enterprise process modeling, analysis of six process flows, and process performance prediction has been implemented to validate the proposed methodology.

Keywords: Dynamic Enterprise Process Modeling, Process Performance Evaluation, Process Measurement, Flow Analysis and Prediction

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1. Introduction

In order to manage enterprise businesses effectively, locate problems and areas for improvements quickly, enterprise decision makers need to use sophisticated process modeling and management tools to understand business processes from various perspectives supported by an intelligent enterprise information system. Therefore, enterprise modeling and process performance management has been the recent research focus in the development of flexible enterprise information systems.

There have been significant research efforts aimed at improving business process performance such as PDCA (Plan Do Check Act) [1], IDEAL (Initiating Diagnosing Establishing Acting Learning) [2], QIP (Quality Improvement Paradigm) [3], and the CMM (Capability Maturity Model) [4]. As to the research of evaluation measurement approaches for process performance, the GQM (Goal Question indicator Measures) methodology was introduced by Basili *et al.* [5] in 1988, refined by AMI [6] in 1992 and by Pulford *et al.* [7] in 1996, and was applied to the goal-driven software evaluation by Park *et al.* [8] in 1996. Especially, Mendonca *et al.* [9] converted the GQM to another Goal Question Metric for improving evaluation processes in 1998.

How do we evaluate business processes in an enterprise? The answer to this question is the basis of enterprise process simulation and optimization research for business process improvements [10]. BPR (business process reengineering) is an important concept that was firstly proposed by Hammer [11] in 1990. The fundamental definition of BPR, proposed by Hammer in [12], is that starting from the very basic issues, reformation of the reengineering process will dramatically improve an organization in terms of its *cost, quality, service*, and *speed*. Therefore, improvement and reengineering of a process is a fundamental tenet of BPR. Cheng *et al.* [13] refined the definition and description of process reengineering and proposed the CMPR (Construction Management Process Reengineering Method). In their studies, they discussed the customer satisfaction issue and analyzed the cost-structure index of activities. Fitzgerald *et al.* [14] proposed a determinant framework from results (financial performance, competitiveness) and determinate items (quality, flexibility, resource utilization, innovation) in a service business. Lynch *et al.* [15] presented a performance pyramid for performance measurement from various metrics as vision, market, financial, customer satisfaction, flexibility, productivity, quality, delivery, cycle time, and waste. The structural AMBITE performance measurement cube [16] presents three measurement dimensions of business processes, competitive priorities, and manufacturing typology, and it measures enterprise performance from time, cost, quality, flexibility, and environment perspectives. Folan *et al.,* [17] described the evolution of performance measurement (PM) at four levels: recommendations, frameworks, system and inter-organizational performance measurement. They proposed that the performance measurement leans towards performance management, and considered process performance management as a future research area.

Virtual enterprises and supply networks consist of multiple organizations. Although various distributed mechanisms have been proposed for supply networks and virtual enterprises, they may not be effective for supply networks because of the difficulties of scheduling tightly related supply operations and handling the massive uncertainties that are involved. Feng *et al.*[18] explored a price-based multi-agent scheduling and coordination framework for supply networks and carried out a systematic experimental study to validate the proposed framework. Zribi, *et al.* [19] proposed a hierarchical method for the flexible job-shop scheduling problem, which was mainly adapted to a job-shop problem with high flexibility and was based on the decomposition of the problem in an assignment sub-problem and a sequencing sub-problem. Shen *et al.* [20] proposed an *iShopFloor* concept based on Internet, Web, and agent technologies, applied this concept to distributed manufacturing scheduling primarily at the shop floor, and showed the feasibility of applying it in virtual enterprises and supply networks. A detailed literature review of agent-based distributed manufacturing process planning and scheduling can be found in [21].

Malu and MingChien, *et al.,* presented a comprehensive and automated approach to intelligent business process execution analysis by applying process data warehouse and data mining techniques to process execution data [22, 23].

This paper presents a methodology towards business process intelligence in process performance management. Especially, measurement models for analyzing six process flows during enterprise process execution and an evaluation architecture using *time, cost, quality, service, efficiency, speed,* and *importance* for an enterprise process evaluation are proposed and discussed in detail. A prototype system has been developed and applied to a case study to validate the proposed methodology.

The rest of this paper is organized as follows: Section 2 describes some key concepts as well as the proposed architecture of business process intelligence towards process performance management; Section 3 presents a case study in a design process; Section 4 concludes the paper with perspectives.

2 Business Process Intelligence Methodologies and Implementation

From recommendations to frameworks, system, and inter-organizational performance measurement (IOPM), IOPM is the highest step of performance measurement (PM), and it emphasizes process performance management [17]. Amaratunga and Baldry [24] defined performance management as the use of performance measurement information to realize positive changes in organizational culture, systems and processes by setting agreed-upon performance goals, prioritizing activities and allocating resources, informing managers to either confirm or change current policies or program directions to meet these goals, and sharing performance results in pursuing those goals.

Figure 1 shows a simplified schematic representation of the performance management process depicted by Smith, *et al.,* [25]. The representation contains three steps: measurement, analysis and response, which are carried out within an organization and influenced by the external environment. All these steps are controlled by manager's strategies according to the conditions of an organization and its related external environment.

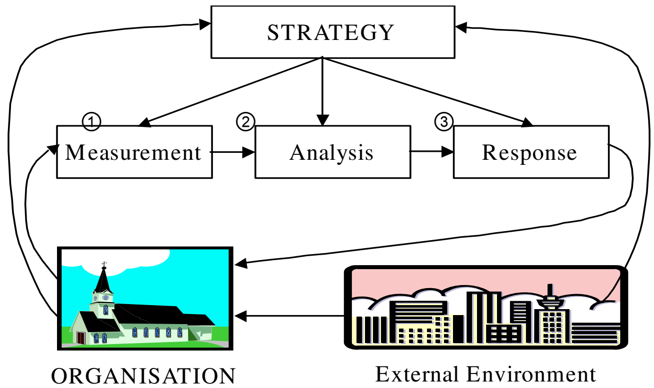

Fig. 1. Schematic representation of the performance management process

Based on the above performance management process, we propose a schema of business process intelligence towards a performance management system, as showed in Figure 2. In the implementation of the proposed system, there are two ways to realize *measurement*: (1) Using *process simulation* (P.Sim) to obtain the metric data and simulation information of a virtual organization. This requires that the enterprise process models be defined by the *process definition environment* (P.Def). (2) Using process enactment technology or a conventional management information system to get the actual enterprise execution information for measuring the performance of business processes. It is called *process measurement* (P.Measurement).

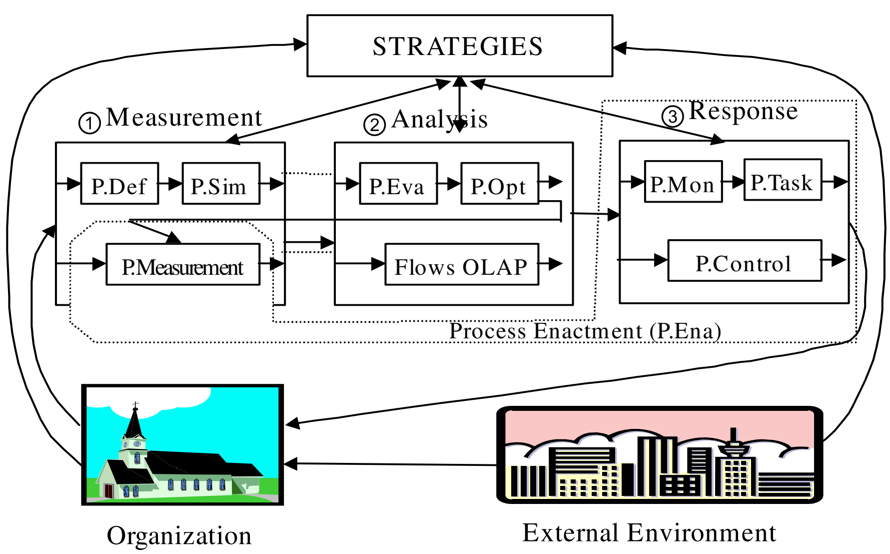

Fig. 2. Schema of business process intelligence towards performance management

There are two ways to realize the analysis step:(1) automatic business *process evaluation* (P.Eva) and *process optimization* (P.Opt); (2) Online Analytical Processing of process flows (Flows OLAP) on the metric data and the information in the process data warehouse. Similarly, the *Response* step includes process monitoring followed by process task scheduling and process control.

The details are discussed in the following subsections. Section 2.1 presents the measurement models for six process flows analysis; Section 2.2 proposes an enterprise process evaluation methodology; Section 2.3 presents the actual system architecture and functions of business process intelligence.

2.1 Six Process Flows

In order to understand better the measurement models, we need to introduce some key concepts related to enterprise process engineering. The TCM (Total Cost Management) [26] approach is based on the belief that an in-depth understanding and the continuous improvement of the business process are the driving forces behind effective management of costs. ABM (Activity-Based Management) is widely adopted to address these issues because it provides a complete picture of profits and costs of doing business compared to traditional cost accounting methods. Business process measurement and evaluation are the foundation of business process improvement in the ABM approach. They are also the organizing techniques for improving performance measurement and decision support functions within an organization. In order to realize business process evaluation, an integrated enterprise process modeling framework should be determined. Based on traditional ABM solutions, we offer integrated capabilities in data management, analysis, cooperative control, and behavior description. In the proposed solution, evolved from the SADT and COSMOS model [27], an enterprise model architecture is proposed [28, 29] by referencing the CIMOSA [30]. It is a tri-dimensional framework including the view dimension, the generality dimension, and the lifecycle dimension.

In the view-dimension, an enterprise can be effectively described from five aspects: process, infrastructure, behavior, cooperation, and information as

$$E_M = \langle P_M, I_M, B_M, C_M, I_{FM} \rangle. \quad (1)$$

where P_M: Process Model; I_M: Infrastructure Model; B_M: Behavior Model; C_M: Cooperation Model; I_{FM}: Information Model.

P_M is the core of the enterprise model. It is a partial set of business activities with the relative resource supports, inputs, outputs, and controls, described as:

$$P_M = \langle \boldsymbol{A, P, R, Control, Support, Input, Output} \rangle \quad (2)$$

where $\boldsymbol{A}=\{a_1,a_2,\ldots,a_m\}$ is a set of activities; $\boldsymbol{P}= \{Product_1,Product_2,\ldots,Product_j\}$ is a set of products; $\boldsymbol{R}=\{r_1,r_2,\ldots,r_k\}$ is a set of resource types; ***Control*** is the tangible and intangible control relationships; ***Support*** is the relationship of resources for an activity, and $\boldsymbol{Support} \subseteq \boldsymbol{A} \times \boldsymbol{R}$; ***Input*** is the relationship of input products to an activity, $\boldsymbol{Input} \subseteq \boldsymbol{A} \times \boldsymbol{P}$; ***Output*** is the relationship of output products to an activity, $\boldsymbol{Output} \subseteq \boldsymbol{A} \times \boldsymbol{P}$.

The infrastructure model, behavior model, cooperation model, information model, and some technology issues in the generality dimension and the lifecycle dimension, such as zero-time enterprise modeling and zero-time process optimization technology, was discussed in literature [28,29,30]. In the following subsections, we will discuss the measurement models for six process flows.

2.1.1 Activity Flow

Activity flow represents the execution order of activities in the enterprise process life cycle, which includes activities' time order and the structural relationship of activities. The latter can be defined as the structure of the process model. The former could be illustrated within a Gantt chart. *Activity flow* embodies the parallelism among activities in enterprise processes, such as structure parallelism and run-time parallelism. *Activity flow* is the baseline of enterprise business processes and other stream information are derived from it. Activity flow analysis can be used to support enterprise concurrent engineering and collaborative business management.

2.1.2 Information Flow

There are two types of information flows: *product information flow* and *data flow*. Like activity, *product information flow* has two aspects. From the vertical aspect of the enterprise process, i.e., from the beginning to the end of a process, *product information flow* indicates the generation relations between products. The generation of a products' tree structure can be referred from the sub-process model by process tracking. It serves as a producing history, supporting quality improvement and the tracking of the producing responsibility of products. From the horizontal aspect, i.e., upon the input or output of an activity in an enterprise process, *product information flow* shows its product heap state. The product heap quantity queue in the horizontal product flow can be used to study "Zero Inventory" and "Just-In-Time" inventory management. It can reflect the cooperative degree/balance between producing activity and consuming activity for the product.

Data flow is a time sequence to describe the data changes in the behavior model and database or file system. It is ordered by time and used to verify process execution. Similar to the *product information flow*, the data generated by the activities from start to stop of a process execution form a horizontal *data flow,* which can be used for analyzing the operations of the behavior model within a process model. The data at one particular point, varying over time within the process model, are a vertical *data flow* for analyzing the function of the behavior model in an enterprise model. In fact, enterprise supply chain management is a spread of analysis and management of *product information flow* and *data flow.*

2.1.3 Resource Flow

Resource flow indicates resource utilization varying with time in the execution of enterprise processes. For example, resource flow on personnel is called personnel flow. The resource consumption is defined in the specification of resources related to an activity. Thus resource flow can be calculated on the basis of activity flow. The difference between information flow and resource flow is that resources only support activity operations, and cannot be changed and processed as information or material products. Therefore, *resource flow* only focuses on the horizontal aspect, *i.e.*, to calculate the utilization of all kinds of resources during an enterprise process execution.

Definition 1. For a resource $r \in \boldsymbol{R}$, $ActsSupported(r)=\{x|x \in A \wedge <r,x> \in Supporting\}$ is called relative activity set of resource r.

Definition 2. For an activity $a \in \boldsymbol{A}$, a set of cloning activity[1] [28] of a in time t is:

$$ActiveClone(a, t) = \{ LT(ISet(a)) \mid LT(ISet(a)) \leq t \leq LT(ISet(a)) + d(a) \} \quad (3)$$

where $d(a)$ is the duration of a; $ISet(a)$ is the input product set of a; LT is the last completion time of the products in $ISet(a)$, which represents a cloning activity element.

Definition 3. At time t, the utilization of resource r occupied by an activity $a \in \boldsymbol{A}$:

$$ResUsed(a,r,t)=\text{card}(ActivitClone(a,t))*NUsed(a,r) \quad (4)$$

where card($ActivitClone(a, t)$) is the cardinal number of $ActivitClone(a, t)$, i.e., the number of the elements in the set $ActivitClone(a, t)$; $NUsed(a,r)$ is the utilization of r when a runs.

Definition 4. The consumption of resource r for all $r \in \boldsymbol{R}$ in process ps at time t is:

$$NumOfRes(ps,r,t) = \sum_{i=1}^{n} ResUsed(a_i, r, t) \quad (5)$$

where N=card($ActsSupported(r)$), i.e., the number of activities related to resource r; a_i is ith activity related to resource r. The discrete order of the resource consumption varying with time is called the resource flow for r.

2.1.4 Cost Flow

Cost flow is a time order of the expense of a business process. In general, cost flow may be divided into resource usage costs and source product costs (i.e., material cost). It is used to show the costs that happen during the life cycle of a process.

Definition5. For $r \in \boldsymbol{R}$，$ResUnitCost$: $\boldsymbol{R} \rightarrow \boldsymbol{R}+$ is the unit cost relation on $\boldsymbol{R}$. It is signed as $ResUnitCost(r)$.

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[1] Concept of ‘‘cloning activity’’ is a kind of the concurrence activity. If the inputs have more matched groups and the supports have more matched groups, the activity can be activated more times.

Definition 6. The effective cost of r, $r \in \boldsymbol{R}$, related to a process *ps* in $[t_1, t_2]$, can be calculated as follows:

$$Cost(ps,r,t_1,t_2)=ResUnitCost(r)\times\int_{t1}^{t2} NumOfRes\ (ps,r,\ t)dt \qquad \textbf{(6)}$$

where $NoR(ps,r,\ t)$ is the resource usage of r in the *ps* at time t. It could be obtained from formula (5).

Definition 7. *Total Resource Cost* is the cost consumption for all kinds of resources supporting business activities during the *ps'* execution in $[t_1, t_2]$. It can be calculated as:

$$TResCost(ps,\ t_1,\ t_2)=\sum_{i=1}^{n} Cost(ps,\ r_i,\ t_1,\ t_2\ ) \qquad \textbf{(7)}$$

where $n=card(\boldsymbol{R})$ is the cardinal number of resource set related to the process *ps*, i.e., the number of resource classes defined in the process *ps*; *Cost* is the cost of one kind of resource r_i used in process *ps* in $[t_1,t_2]$.

Definition 8. *Source product set* in *ps* is defined as:

$$SPS(ps)=\{sp|sp\in P\wedge(sp\ \mathrm{IN}\ ps)\wedge\neg(\exists a\ (a\in \boldsymbol{A}\wedge\langle a,\ sp\rangle\in Output))\} \qquad \textbf{(8)}$$

For partial order set $<\boldsymbol{A}\cup\boldsymbol{P},\ \boldsymbol{Input}\cup\boldsymbol{Output}>$, *SPS* is the maximal set of the source products in the process *ps*.

Definition 9. For a source product *sp* in the process *ps*, $sp\in SPS$, there is a mapping function *SProdCost*: $\boldsymbol{P}\rightarrow\boldsymbol{R}^{+}$, which is called the *unit cost function* of source product, signed as *SProdCost*(*sp*).

Definition 10. In $[t_1,t_2]$, *Source product cost* in process *ps* can be calculated using the formula:

$$SouCost(ps,t_1,t_2)=\sum_{i=1}^{m} SProdCost(sp_i\ )\times NPurc\ (\ ps,\ sp_i,\ t_1,\ t_2) \qquad \textbf{(9)}$$

where $m=card(SPS)$; $sp_i\in SourceProducts$ in process *ps*; $NumPurc(ps,\ sp_i,\ t_1,\ t_2)$ is the purchase quantity of source product sp_i in $[t_1, t_2]$, it is a statistical value. In the simulation environment, source products are created by the generation of random numbers according to the specific distribution of source product arrival frequency.

Definition 11. *Process Effective Cost* in $[t_1,\ t_2]$ can be calculated as follows:

$$Pcost(t_1,t_2)= SouCost(ps,t_1,t_2) + TResCost(ps,t_1,t_2) \qquad (10)$$

In process execution (via simulation or enactment), the consumption of source products and resources utilization is recorded and collected. Process effective cost can be calculated and thus cost flow is generated.

2.1.5 Cash Flow

Cash flow[2] is a measure of a company's financial health. It equals cash receipts minus cash payments over a given period of time; or equivalently, net profit plus amounts charged for depreciation, depletion, and amortization.

Cash flow is the amount of cash varying during enterprise process execution. Here we focus on discussing the income of the enterprise. A complete enterprise process model should consist of various sub-processes such as the main production plan, product design, manufacturing, finance management, human resource management, material purchasing and product sales and so on. The sale sub-process is a part of the process model and all the incomes can be obtained in this process from customers.

For an intermediate product, its cost can be calculated by adding its source products' cost and the producing cost of all the activities from its source products to itself. Using this method, all end products' costs can be obtained, thus forming the cash flow in an enterprise process.

To analyze the amount and the features of *cash flow* for an enterprise, we need to discuss the *income* in the sale sub-process. All the end products in this sub-process are called goods, and the sale prices can be defined in the specification of goods according to their costs.

Definition 12. The goods set in the process *sale* are a set of end products, which can be described as:

$$Gds(Sale)=\{\ p \mid p\in P\wedge (p \ \text{In}\ Sale) \wedge \neg(\exists a\ (a\in A\ \ \wedge \langle a, p\rangle \in Input))\} \qquad \textbf{(11)}$$

For the partial order set <***A*** ∪ ***P, Input*** ∪ ***Output***>, *Gds*(*Sale*) is the maximal number set in the process *sale*.

Definition 13. For any goods $p \in Gds$, there exists a Goods-Price function *Price*(*p*)

[2] http://www.investorwords.com/768/cash_flow.html

denoting the mapping relation, ***Price*****:** ***P*****→*****R***+.

Definition 14. In [t_1, t_2], the sale income for the process *ps* can be obtained by following:

$$Income(ps,t_1,t_2) = \sum_{i=1}^{m} Price(p_i) \times NSale(ps,t_1,t_2,p_i) \quad \textbf{(12)}$$

where k=card (*Gds*); $p_i \in Gds$; $NSale(ps,t_1,t_2,p_i)$ is the sold amount of the Goods p_i in [t_1,t_2], which can be calculated from simulation or execution.

2.1.6 Profit Flow

A company's profit is the positive gain from an investment or business operation after subtracting all expenses. It is the opposite of loss. Net profit is calculated by subtracting a company's total expenses from total revenue, thus showing what the company has earned (or lost) in a given period of time (usually one year). It also called net income or net earnings.[3]

Definition 15. For a process *ps* in [t_1,t_2], enterprise profit can be calculated by:

$$Profit(ps,t_1,t_2)=Income(ps,t_1,t_2) - Pcost(ps,t_1,t_2) \quad (13)$$

where $Income(ps, t_1,t_2)$ is the sale income of a process *ps* in [t_1,t_2]; $Pcost(ps, t_1,t_2)$ is the cost of a process *ps* in [t_1,t_2]; They can be calculated by formula (10) and (12).

By dividing the execution time of the enterprise process into *n* time sections and calculating profits in each section, we can get cash flow and profit flow in the enterprise process. The prediction of cash flow or profit flow is the key for an enterprise to make decisions on investment and process reengineering. In order to make such decisions, the first thing is to estimate the economical lifecycle of an enterprise, following which is the calculation of income and expenditures in each time section throughout the lifecycle.

During enterprise process execution, in addition to the investment and outcome for a process, enterprise profits are affected by some elements from external environments, such as management and revenue policies. Therefore, *profit flow* describes the actual profits for the enterprise.

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[3] http://www.investorwords.com/3880/profit.html

2.2 Dynamic Enterprise Process Evaluation Methodology

During enterprise modeling, the proposed evaluation method supports the following two kinds of enterprise process dynamic modeling: stream-like and project-oriented. The former is characterized by a random discrete sequence to describe a specific distribution of source product arrival frequency. It can be used to describe the processes in mass production. The latter is a kind of process activated by a set of events and terminated by an event from the process. It is suitable to describe engineering projects or a single-piece production.

To evaluate different types of processes, different evaluation criteria have to be considered. The proposed evaluation system (P.Eva) enables dynamic analysis and evaluation of the enterprise process from *time*, *cost*, *quality*, *service*, *efficiency*, *speed*, and *importance*. The enterprise processes evaluation process can be illustrated as Figure 3. In order to evaluate enterprise processes, the enterprise-level decision model needs to be defined such as enterprise objectives and their weights, and business process's *importance*.

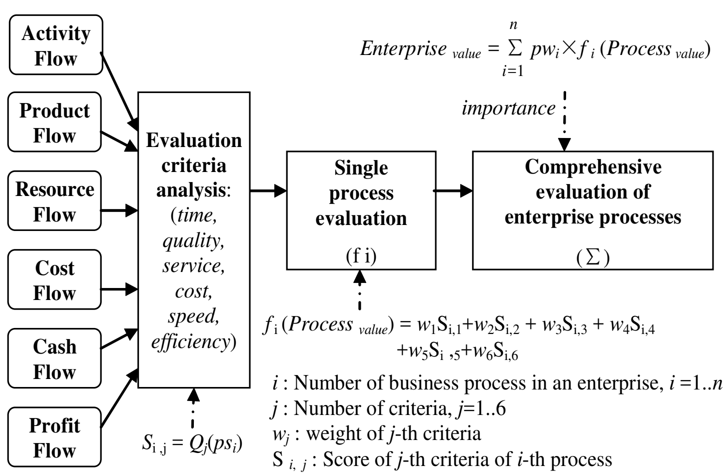

Fig. 3. Schematic representation of a comprehensive evaluation of enterprise processes

Section 2.2.1 focuses on discussion of the above criteria and the evaluation model. *Time, quality, service, efficiency* and *speed* are the evaluation criteria of enterprise process performance, and *cost* is the economic evaluation criterion. As a weight coefficient of process evaluation value, *importance* will be used for a comprehensive evaluation of enterprise processes and will be discussed in Section 2.2.2.

2.2.1 Evaluation Models for Enterprise Processes

Process performance evaluation is related to activity flow, product flow and resource flow. Therefore, process performance evaluation criteria consists of *Time* (process duration utility), *Service* (customer satisfaction), *Quality* (cost structure utility), *Speed* (product heap utility), and *Efficiency* (resource usage utility).

Time means time-to-market. Here, it is the process duration utility generated from the activity flow:

$$Time = Q_t(ps) = \frac{1}{m}\sum_{i=1}^{m}\frac{\left|\sum_{j=1}^{n} D(a_{i,i}) - T\_ex_i(ps)\right|}{T\_ex_i(ps)} \quad (15)$$

where m is the number of end-products in the process ps; T_ex_i is the expected duration for the ith product in ps, and it can be referred from the result of simulation or static PERT/CPM; $D(a_{ij})$ is the real duration of the j-th activity on the *main-time-critical path* [30] of the i-th product in ps. The average of all end-products' *time* utilities is the whole *time* utility of ps.

Speed is a measurement of the capability of enterprise processes. It is the capability of all activities characterized by *Product Heap Utility* or the time of the input products waiting for handling by activities defined in *Stream-Like* process ps. It can be calculated according to *product flow* in ps, as follows:

$$Speed = Q_s(ps) = \frac{1}{m \times n}\sum_{i=1}^{n}\left(\sum_{j=1}^{m} Q\_L(p_i, t_j) / L(p_i)\right) \quad (16)$$

where $Q\_L(p_i, t_j)$ is the queue length of a mid-product p_i at time t_j; $L(p_i)$ is the expected security value for the product p_i in ps; m is the number of the time section that the whole execution-time of the process *ps* can be divided; *n* is the number of intermediate products. The average of the ratio of *n* product number to the expected security values is called the *speed index* of process *ps*.

As a *resource usage utility*, ***Efficiency*** is the measurement for resource utilization during the execution of the process *ps*. It is an important index for the evaluation of the enterprise process. It can be obtained from the resource flow in process *ps*, using the following formula:

$$Efficiency = Q_e(ps) = \frac{1}{k \cdot m} \sum_{i=1}^{k} \sum_{j=1}^{m} (RN(r_i) - NoR(r_i, t_j)) / RN(r_i) \qquad (17)$$

where k=the number of resource types in process *ps*; m is number of sections which the whole project cycle can be divided; $RN(r_i)$= the available amount of resource r_i; $NoR(r_i,t_j)$=the actual usage at time t_j, it can be referred to formula (5).

Efficiency represents the resource usage utility of a process, and can be calculated using the average of all resource utilization at each time-section. The lower the value of *Efficiency*, the higher the efficiency of the resource.

Service is a measurement of customer satisfaction. To satisfy customer needs, the functional target of a process should be customer-oriented [13]. A company's operation can be viewed as a serial composition of processes. Each process has its targets to achieve. In this framework, it is essential to combine company policies with the targets of each process in order to accomplish the company's policies. Before process analysis, the operations policies of a company must firstly be defined. The inclusion of policy demands is also essential to the realization of a company's operations policies and the customer needs. The main steps of the evaluation process are described as follows:

(1) *Determination of Process Target's Weight*

This study has developed a target attainability matrix for transforming company policies and customer demands into targets of the processes. The score of the relative importance (w_i) of each process target can be calculated using the following formula:

$$w_i = \frac{\sum_{j=1}^{m} r_{ij} \times p_j}{\sum_{i=1}^{n} \sum_{j=1}^{m} r_{ij} \times p_j} \qquad (18)$$

where w_i = relative importance weight for process target i; m = number of customers' demands; n = number of process targets; i is the index of process targets; j is the index of customer demands; r_{ij} = corresponding rating between i-th process target and j-th customer demand (r_{ij} =1,3,5); and p_j = emphasis degree of j-th customer demand (p_j =1..5).

The score of the process target (w_i) represents the degree of satisfaction that the process target delivers to the customer. The higher the score of w_i, the more the customers' satisfaction completed.

(2)*Analysis of Process Target Achievement*

A quantitative method is used to calculate the achievement of each process target that the operational functions complete. In the process definition environment (*P.Def*), some properties need to be defined in each activity, such as the mapping of activities to process targets (i.e., application components) and the attainability of each activity for each process target A_{ik} (0~10/10) evaluated by the senior managers. Using this information, the process target achievement matrix (PTAM) can be built on the basis of the process model, and the process target attainability, PA_i (0~w_i), achieved by the process activities, can be calculated. The total process attainability (*Service*) of the targets endowed by each activity and the degree of contribution (C_k) endowed by each activity are also identified. The equations for calculating PA_i , *Service* and C_k are demonstrated as follows:

$$PA_i = \sum_{k=1}^{g} w_i \times A_{ik} \qquad (19)$$

$$Service_{index} = 1 - \sum_{i=1}^{n} PA_i \qquad (20)$$

$$C_k = \sum_{i=1}^{n} w_i \times A_{ik} \qquad (21)$$

where g=number of process activities; n=number of process targets; PA_i=attainability of i-th process target achieved by the process activities; A_{ik}= activity$_k$'s attainability of the i-th process target; *Service* = total attainability of process to the targets (*Service*=0~1); and C_k = contribution of activity$_k$.

PA_i , *Service* and C_k can be used as indices for process evaluation. PA_i represents the process attainability of a certain process target, and the higher the value of PA_i, the more probable the attainability. *Service* represents the utility of total attainability of the process, and the lower the value of *Service*, the more suitable the operational function related to the process targets, and the higher customer satisfaction about the process. C_k represents the contribution of a certain operation to all process targets; the higher the value, the greater the contribution, which also means that the function is more likely to satisfy customer demands.

Quality is used to analyze the cost structure of activities. In addition to analyzing process target achievement, we have to discuss the cost structure of activities in the process model. As another important factor of process evaluation, ***Quality*** mainly concerns the characteristic of process structure such as the ratio of value-added and non-value-added, and primary and secondary. Generally speaking, the higher the cost efficiency of transforming the process cost into the value of the external customers, the better the quality of a process; and the higher the cost efficiency of the process in supporting the primary activities to achieve their targets, the better the quality of a process.

According to ABM technology, an activity whose producing value is of use to external customers is called a value-added activity, and the opposite activity is called a non-value added activity; a primary activity is a direct supporting task of a process, and the opposite activity is called a secondary activity. So, during the enterprise process modeling, modeling engineers have to define these characteristics for each activity. The total cost of the process can be calculated using formula (10). In the same way, we can get the total cost of value-added activities and primary activities, respectively, only by restricting the computing domain for activities. The value-added index and primary activity cost index can be calculated using following formulas:

$$V_{index} = \frac{T_{\mathrm{cova}}}{T_{\mathrm{Pcost}}} \qquad (22)$$

$$P_{index} = \frac{T_{\mathrm{cop}}}{T_{\mathrm{Pcost}}} \qquad (23)$$

where V_{index} is a value-added index and represents the cost efficiency of a certain process that satisfies the external customers' demands; T_{cova} = total cost of value-added activities; T_{Pcost} = total process cost; P_{index} is a primary activity cost index and depicts the cost efficiency of the process in supporting the primary activities to achieve their targets; T_{cop} =

total cost of primary activities.

Process cost structure index, i.e., process quality index, can be obtained as follows:

$$Quality = Q_q(ps) = w_v \times (1 - V_{index}) + (1 - w_v) \times (1 - P_{index}) \qquad (24)$$

Quality is used to represent the overall score of the process in terms of the cost structure. w_v is the weight used by managers for weighting V_{index} while conducting the process cost structure evaluation. In general, if we are more concerned with customer satisfaction, a lower weighting (w_v) is given.

Process economy evaluation criteria are used to evaluate economic issues such as cost flow, cash flow and profit flow. The difference is that *Quality* puts the emphasis on the analysis of the cost structure of the process, while economy evaluation concerns the relationship between economic flow and market expectation.

In fact, cost flow, cash flow, and profit flow are similar in reflecting process economy evaluation criteria (PEEC). PEEC can be represented using process cost utility, cash flow utility and process profit utility. But, only one of them can be combined with performance evaluation criteria to evaluate the enterprise process. Here, we only discuss the process cost utility.

Process cost utility, ***Cost*** is generated from cost flow, and it is used to represent the total cost utility of the process, as shown below:

$$Cost = Q_c(ps) = \frac{\left| \sum_{i=1}^{m} P\cos t(ps, t_i, t_i + \Delta t) - P\cos t_e(ps) \right|}{P\cos t_e(ps)} \qquad (25)$$

where $Pcost(ps,\ t_i,\ t_i+\triangle t)$ = the running cost of process *ps* in time $(t_i, t_i+\triangle t)$. The process cycle is divided into *m* parts. $Pcost_e(ps)$ is the expectation cost for process *ps*. In general, the smaller the value of *Cost*, the bigger the competitive power of an enterprise process.

2.2.2 Enterprise Processes Evaluation Methods

Single Process Evaluation and Process Redesign**:** During the enterprise diagnosis, we should analyze each process from the aforementioned aspects and give a total evaluation for each process. In general, using linear weighting for each index, a sum of each weighting index is the total evaluation of a specified process.

Process cost utility is used for representing the economic evaluation. A total process evaluation consists of process performance evaluation criteria and process economic evaluation criteria such as *Time, Service, Quality, Speed, Efficiency,* and *Cost*. All of the evaluation objectives, the objective values and the related weighting coefficients must be defined in the enterprise decision model by decision-makers according to their significance. A total process evaluation $Process_{value}^{i}$ can be calculated as follows:

$$Process_{value}^{i} = f(ps_i) = w_1 \times Time_i + w_2 \times Service_i + w_3 \times Quality_i + w_4 \times Speed_i + w_5 \times Efficiency_i + w_6 \times Cost_i \quad (26)$$

where w_1~w_6 are the weights for the related evaluation criteria, and $\sum w_j = 1$, j=1..6. The smaller the value of $Process_{value}^{i}$, the better the process model.

The analysis results derived from the process evaluation system can be used to identify the major defects of the process. According to process target attainability (PA_i), the satisfaction measure of customers' demands can be identified and whether new activities are required can be determined. Process contribution (C_k) is an index that measures the contribution of each activity to the process. The value-added index (V_{index}) is applied to determine the cost efficiency of transforming the process cost into the value of the external customers. The primary activity cost index (P_{index}) is used to examine the cost efficiency of the process in supporting the primary activities to achieve their targets, and forms a basis for process management. The process value $Process_{value}^{i}$ is a function of a process structure performance and economical criteria, which can be calculated by formula (16) with *Service*, *Time*, *Speed*, *Efficiency*, *Cost* and *Quality*. $Process_{value}^{i}$ is an index to determine whether or not process reengineering is necessary.

***Integrated Evaluation for Enterprise Processes*:** In a complex enterprise, usually, there are many processes with different business targets. How do you evaluate them? As we know, different business processes usually have different levels of importance. According to each process' $Process_{value}^{i}$ and its *importance*, our dynamic evaluation system of enterprise process can give a total evaluation, and the analysis result of redesign. The integrated evaluation of enterprise processes can be calculated as:

$$Enterprise_{value} = \sum_{i=1}^{n} pw_i \times Process_{value}^{i} \quad (27)$$

where pw_i = the *importance* of the *i*-th business process; $Process_{value}^{i}$ = the evaluation value of the *i*-th business process; n= the number of business process; $Enterprise_{value}$ is the integrated evaluation for enterprise processes.

2.3 System Architecture and Functions

2.3.1 Architecture of Business Process Intelligence

Business process intelligence, (BPI) based on dynamic enterprise process modeling (DEPM) and process data mining (PDM) technology, facilitates the enterprise decision-makers with an intelligent analysis for business process evolution, of which most main components have been implemented in the Software Engineering Institute of BeiHang University in China, such as the following four subsystems: process definition (P.Def), process simulation (P.Sim), process optimization (P.Opt), and process enactment (P.Ena).

Figure 4 illustrates an architecture of BPI towards process performance management and the evolutionary process of an enterprise process along the direction of yellow colored arrows. In Figure 4, from bottom to top depicts the process of business processes data to be mined for process flow analysis. Now, we begin to introduce BPI mainly focused on DEPM, PDM and flow analysis and prediction.

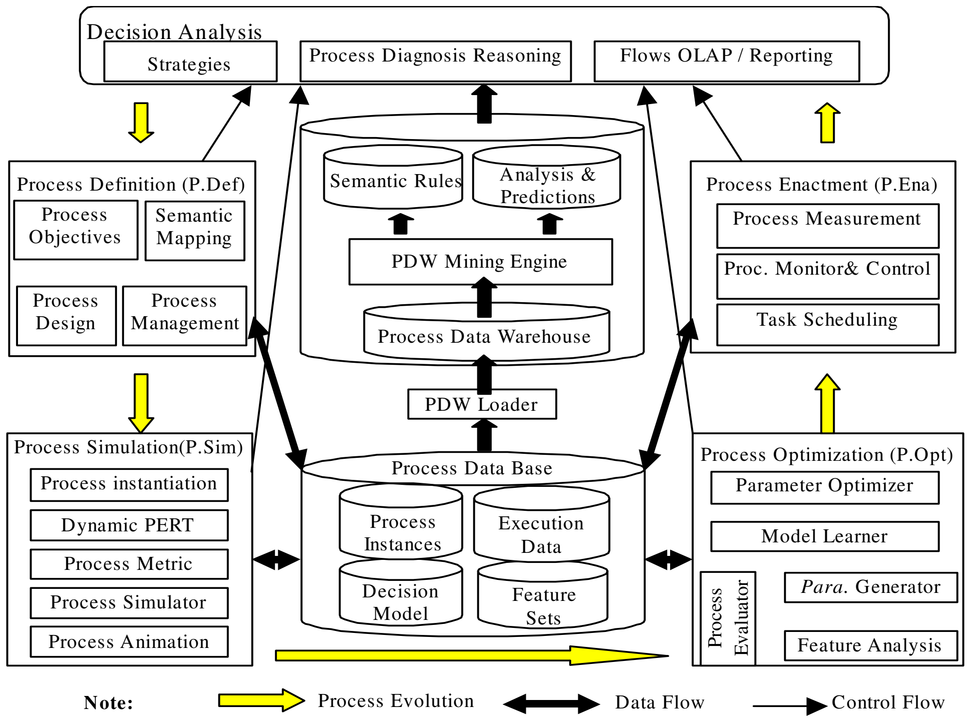

Fig. 4: System architecture of business process intelligence towards process performance management

2.3.2 Functions of Business Process Intelligence

2.3.2.1 Dynamic enterprise process modeling **(DEPM)**: Process definition, process simulation, process optimization and process enactment are the four key technologies of DEPM.

P.Def includes *Process design tool, process management, process objectives*, and *process semantic mapping*. *Process design tool* is a set of graphical editors with the capability of syntax and semantics checking. *Process management* is responsible for generating an instance model, according to its specific definitions, and model instances management and supporting rapid modeling, based on the component base and the reference models of industry sectors. *Process objectives* and *process semantic mapping* provide the functions of the enterprise process objective definition and the process semantic description and mapping.

The function of P.Sim is to analyze an enterprise process instance and provide the dynamic enterprise process information to the enterprise managers and P.Opt. P.Sim contains process instantiation, simulator, dynamic PERT, process metric and animation etc.

P.Opt is a process optimization tool using a FR-TS algorithm [32]. It consists of process evaluation, a model learner, a process parameter generator, feature analysis, and a parameter optimizer. The outputs of P.Opt include a set of optimized process models and a recommended process model to assist decision-makers. The selected optimal process model can be enacted in P.Ena for enterprise process monitoring and controlling.

All functions in the response step are integrated in P.Ena such as process measurement, process task scheduling, process monitoring and control. During process operation, some new requirements will be fed back to P.Def via Strategy if a change in its external environment is detected and the process needs to be improved.

The measurement of the various process flows such as activity flow, product flow, resource flow, and cost flow is implemented in P.Sim. *Process evaluator* (P.Eva) is necessary to assist enterprise managers to analyze, evaluate and optimize business processes. It analyzes the metric data generated by process simulation according to the proposed methodologies in Section 2.3, and generates a total process evaluation value for enterprise processes according to the business features and the decision model.

Two core components, *model learner* and *parameters optimizer,* are implemented in P.Opt. *Model learner* receives the training set prepared by *process evaluator* as inputs. A learning algorithm called *Fletcher Reeves* is applied to learn from this data set. *Model learner* can learn to approach the local optimal solution (*LocBest*) along the direction of seeking optimization, and the local worst solution (*LocBad*) in the opposite direction. The area, from the *LocBest* to the *LocBad*, is a taboo domain for the next seeking optimum. We call it a *Tabu-Region*. *Parameter optimizer* uses an expanded *Tabu Search* algorithm to implement global optimization. In this algorithm, using the concept of *Tabu-Area* (linked with multiple Tabu-Regions) can speed up the process optimization. The integration of the above two methods is called *FR-TS* algorithm. Using the *FR-TS* algorithm, we can track process model evolution [32].

***2.3.2.2 Process data warehouse* (PDW) *and Data mining engine*:** There has been tremendous growth in the area of data management and decision analysis during the last few years. The growth is primarily in the direction of data integration for providing accurate, timely, and useful information. Data warehousing is playing a major role in the integration process. Construction of a data warehouse is generally based on a data warehousing process (DWP) methodology [33]. Currently, there are a good number of methodologies available in the data warehousing area. The reason for this is the lack of any centralized attempts at creating platform-independent DWP standards. The development of such standards is very important. Sen and Sinha [34] reviewed 30 commercial data warehousing methodologies and analyzed the standard practices they have adopted with respect to DWP. It provides valuable insight into the prevailing standard practices for different DWP tasks—system development, requirements analysis, architecture design, data modeling, ETL, data extraction, and end-user application design—and identifies important directions for future research on DWP standardization.

In order to support business process intelligence, we need to build an enterprise's *Process data warehouse* (PDW). PDW contains a wide set of aggregated information describing typical performance metrics. PWD Loader collects data from process instance base with the taxonomy definition, enterprise model information (process, behavior, resource and organization, cooperation, and information), process instance state information (process state changes, resource service state changes, and activity state changes), and process performance metrics. PWD Loader can be activated periodically or upon requests. At loading time, a consistency check is done for process instance data. Data in the PDW can be directly accessed with a commercial reporting tool. Analysts can also use flow OLAP to obtain enterprise processes execution information such as the six process flows.

The PDW mining engine provides a way of "intelligent" analysis and prediction by executing data mining algorithms on the PDW for analysts to understand the causes of specific behaviors and to generate the prediction models that can be used to predict the behavior and performance of a process instance, of the activities, and of the resources. The PDW mining module usually can be decomposed into following four steps:

- *Process data preparation.* A process analysis table needs to be prepared for restrictedly obtaining instances and the behavior information from the PDW for the *classifier*. The process analysis table includes one row per process instance, and indicates where the columns correspond to the "interested" process instance attributes.

- *Behavior analysis preparation.* This phase generates a process- and behavior-specific view joining process analysis and process behavior tables. The obtained view includes all the information required by the classification tool to generate the classification rules.
- *Mining*. A variety of data mining and classification applications are available on the market. We can choose a commercial or off-the-shelf tool. In this step, we have to design and develop a component, *classifier*, mapping the behavior analysis problem into a classification problem. The *classifier* then generates the classification rules and stores them in the "*Analysis and Predictions*" database.
- *Interpretation.* The classification rules can be viewed by analysts in the form of decision trees and can be used to facilitate understanding the causes of certain behaviors. In some cases, analysts may want to repeat the classification after removing some features in the training data set, to force the *classifier* to focus on the specific characteristics in which they are interested.

2.3.2.3 Process Flows OLAP Analysis and Prediction**:** Decision Analysis can be used to assist the manager to choose the reasonable enterprise process model and do reasonable reengineering by flows analysis and prediction.

The process of selecting an appropriate technique for evaluating human and automated systems requires knowledge of the objectives of a task and a realistic environment to assess performance. Howard [35] discussed an approach for predicting system performance resulting from humans and robots performing repetitive tasks in a collaborative manner to enable the systematic estimation of system performance for human–robot scenarios.

Here, in order to give a reasonable explanation for the metric information or future predication, the process diagnosis reasoning tool usually analyzes the tasks (analysis vs. prediction), metric scope (generic vs. user-defined), focus of prediction (targeted vs. untargeted) and status of the instances' subjects by using data mining algorithms. The decision tree for processes analysis and prediction is illustrated as Figure 5.

Process Flows-OLAP Analysis can provide *process flows information statistics* *reporting* and a kind of advanced function of explanations and predictions on a wide variety of process flows metrics and behaviors by using data mining and the application of dynamic PERT [31]. Here, we would like to discuss business process analysis and prediction problems from *scope*, *focus* and *status*.

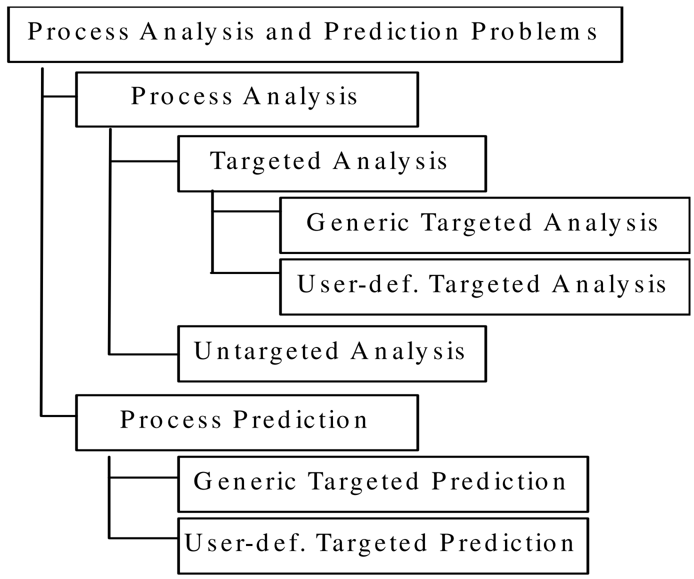

Fig. 5. Classify of processes analysis and prediction.

Process flows analysis refers to the problem of detecting "interesting" behaviors of one or more process executions and of providing explanations for the situations in which such behaviors typically occur.

Analysis on business process execution can be *targeted* or *untargeted*. In a targeted analysis, we ask BPI to explain why a process metric gets a certain value. Process flows analysis may be divided into general targeted analysis and user-defined targeted analysis depending on enterprise characteristics. In some cases, users are interested in finding "interesting" patterns that may be an indication of a situation of which they are not aware.

Process prediction refers to the problem of providing analysts with information about the outcome of a running process instance, or even information about instances yet to be started, such as how many orders will be placed tomorrow or what will be the predicted total order value. Essentially, there are two kinds of metrics that can be analyzed or predicted: general and user-defined. General metrics are applicable to any process, and are required in many analysis scenarios. On the other hand, user-defined metrics are related to aspects that are specific to a particular process or to a group of processes, and cannot be easily generalized.

Predictions about active instances are used for various purposes. For example, they may indicate the likely outcome of a process execution or the expected completion time. If the prediction for an instance indicates that it would not complete in time, then a specified user can be informed, so that he can try to fix up the problem. In some practical scenarios, this involves making telephone calls to the suppliers to ask them to speed up the delivery, or going for air rather than ground shipping. However, even if it is not possible to react to an exception in order to solve the problem, exception prediction information can still be used to take some actions to avoid potential damage.

3. A Case Study

A practical business process, as shown in Figure 6, was used to describe a process of project-oriented process modeling for designing an airplane by using the prototype system to validate the proposed methodology. There are two processes in this business process, namely: *Total Design* and *Draw a design. Total Design* consists of 10 sub processes, namely: 2001, 2002, …, and 2010, to describe the detail processes of the total design process such as integrated design, weight analysis design, geometrical shape design, differential coefficient design, and the pipe design for air entrance and exhaust. Each of these sub-processes has various activities associated with them. The outputs of the total design will be used to draw a design model. Because of secrecy surrounding the airplane design process, we will simply discuss the business process models and some brief information.

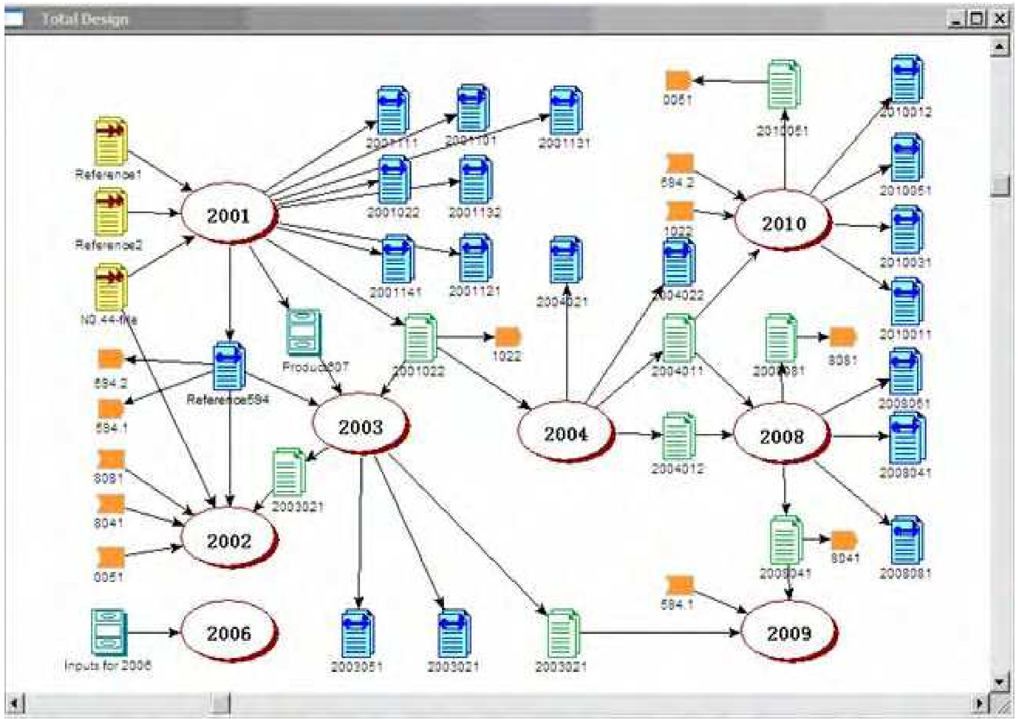

Fig.6. The total design process of an airplane

In a real application, a decision model should be defined first according to the requirements and the characteristics of the industrial sector. Some objectives and the weights can be specified easily and quickly in the decision model editor to adjust the "weight" of different evaluation criteria according to the result of process simulation and the experience. In Figure 7, there are 5 objectives available, and the selected objectives in importance are *Efficiency* (3/10), *Speed* (3/10), *Time* (2/10), and *Cost* (2/10). The predefined time limit is 1000 hours and the cost limit is ￥75685.99. After analyzing the design process, the proposed system can provide a process diagnosis report and some advice for process reengineering and redesign, which are useful in the design process of new airplanes.

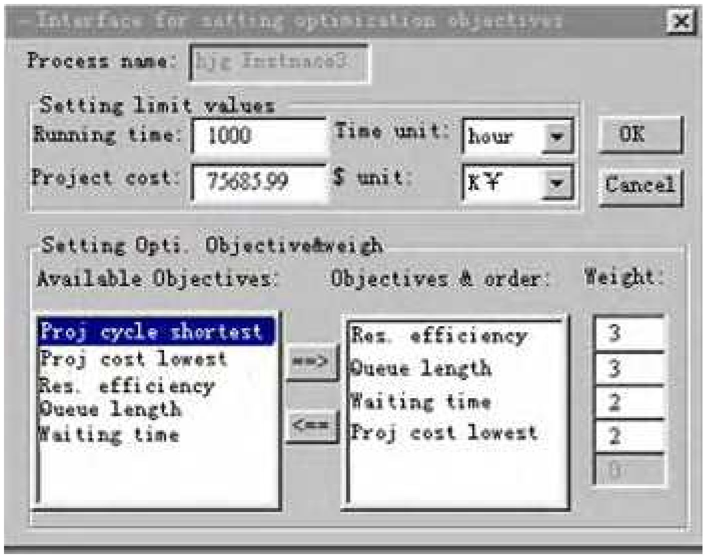

Fig.7. An example of decision model definition

In this case study, we use process simulation and flow analysis technology to get different kinds of data such as an activities Gantt chart, resource efficiency, process cost, and cost flow information scheduled by a four-level scheduling strategies combined with eight kinds of basic rules. Before process simulation, we have to define the coordination rules. Figure 8 illustrates the process of the composite rule definition.

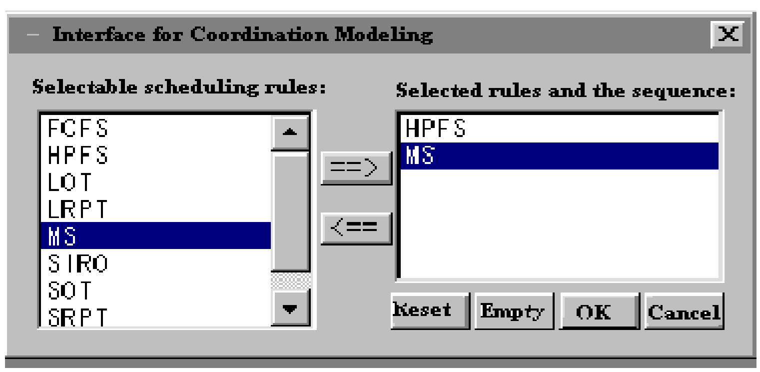

Fig. 8. Interface for Coordination Modeling

As shown in Figure 8, the selectable scheduling rules include these basic rules: HPFS (Highest Priority First Serve), MSFS (Minimum Slack time First Serve), FCFS (First Come First Service), SIRO (Service In Random Order), SOT (Shortest Operation Time), LOT

(Longest Operation Time), LRPT (Longest Remaining Processing Time), SRPT (Shortest Remaining Processing Time) [32]. The process simulation and enactment will execute enterprise processes according to the sequence of selected scheduling rules. HPFS is usually used as the first level rule, while SIRO as the latest level schedule rule. The simulation results indicate: (1) when simulating within the mode of Non-Resource-Matching-Pattern, the simulation result is the best if we select the composite rules HPFS/LRPT/FCFS, and HPFS/MS/* or HPFS/FCFS/SOT is second; (2) For the mode of Resource-Matching-Pattern, the combination of HPFS/MS/* is the best composite rule and HPFS/LRPT/ FCFS is second.

After executing the intelligent optimization module on the airplane design process model, the design process was optimized with the resource reconfiguration. Figure 9 illustrates that using the FR-TS method can rapidly track local optimization, and break through the restriction of seeking the local optimum for the global optimization solution.

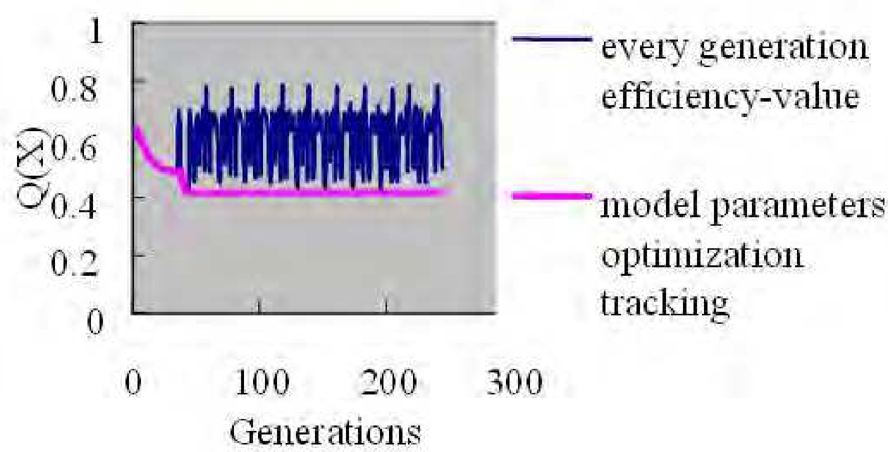

Fig. 9. Q vs Generations using FR-TS method

Compared with the real data of the airplane design process, the duration of the design process can be decreased more than 1250 hours if the design process is scheduled with the combined rule of HPFS/LRPT/FCFS and supported by the process engineering theory with the related software system.

After applying the proposed system in the evaluation of some enterprise processes of manufacturing and service enterprises, we have obtained some conclusions and recommendations as follows; more detailed results can be found in [28]:

- The combined rule of HPFS/LRPT/FCFS is usually suitable for the management of research projects because of no-prediction of research activities;
- The combined rule of HPFS/MS/FCFS is usually suitable for the management of customization projects within the mature techniques such as construction industries; and
- The combined rule of HPFS/FCFS/* is usually suitable for service industries such as hospitality and transportation.

4. Conclusions and Perspectives

This paper systematically presents a set of concepts, technologies, and an approach to business process intelligence towards process performance management, which support enterprise business reengineering and enterprise process flows analysis and prediction. The main contributions of this paper include:

- A set of new concepts and schema of business process intelligence towards performance management;
- Measurement models for six process flows analysis such as activity flow, product flow, resource flow, cost flow, cash flow, and profit flow;
- A dynamic enterprise process performance evaluation methodology using *time, quality, service, cost, speed, efficiency*, and *importance* as seven criteria;
- Validation of the proposed approach through a prototype system supporting dynamic enterprise process modeling and process flows analysis and prediction towards performance management.

As an application software support tool, the proposed performance management system can be used for effectively supporting business process intelligent analysis and business process reengineering in small and medium size enterprises. However, there are currently some limitations for the proposed system in the evaluation of complete and large-scale enterprise processes because of the simulation mechanism which is based on the event queuing theory and specified cooperative schedule strategies for a whole enterprise process in a single-level structure. It cannot describe the difference in schedule strategies for different processes in a large organization. Our future work is to improve the proposed performance management system by combining ontology [36] with the event queuing theory and cooperative schedule strategies using multi-agent technology to implement process ontology [35, 37]. In this way, the different schedule strategies can be defined for different processes, and the simulation of enterprise process will be implemented with a kind of the cooperative simulation of multi-agent systems among the sub-process models and the agent-based process simulation within the sub-process model.

Acknowledgement

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References

[1] W.E. Deming, *Out of Crisis*, MIT Center for Advanced Engineering Study, MIT Press, Cambridge MA, 1986.

[2] B. McFeely, *IDEAL: A User's Guide for Software Process Improvement,* CMU/SEI-96-HB-001, Carnegie Mellon University, Pittsburgh, PA, 1996.

[3] W.A. Shewhart, *Economic Control of Quality of Manufactured product,* D. Van Nostrand Company, New York, 1931.

[4] R. Bate, D. Kuhn, C. Wells, *et al.*, *A Systems Engineering Capability Maturity Model, Version1.1,* CMU/SEI-95-MM-003, Carnegie Mellon University, Pittsburgh, PA, 1995.

[5] V.R. Basili, and H.D. Rombach, The TAME Project: Toward Improvement-Oriented Software Environment, *IEEE Transactions on Software Engineering*, 14(6), 1988, 58-73.

[6] AMI Consortium, *The AMI Handbook: A Quantitative Approach to software Management,* South Bank Polytechnic, London, 1992.

[7] K. Pulford, A. Kuntzmann-Cambelles, and S. Shrilow, *A Quantitative Approach to Software Management: The AMI Handbook,* Addison-Wesley, Wokingham, 1996.

[8] R.E. Park, W.B. Goethert, and W.A. Florac, *Goal-Driven Software Measurement-A Guidebook,* CMU/SEI- 96-HB-002, Carnegie Mellon University, Pittsburgh, PA, 1996.

[9] M.G. Mendonca, V.R. Bhandari, and J. Dawson, An Approach to Improving Existing Measurement Frameworks, *IBM Systems Journal*, 37(4), 1998, 484-501.

[10] C.S. Leem, and I. Kim, An Integrated Evaluation System Based on the Continuous Improvement Model of IS Performance, *Industrial Management & Data Systems,* 104(2), 2004, 115-128.

[11] M. Hammer, Reengineering work: Don't automate, obliterate, *Harvard Business Review*, 1990, 104–112.

[12] M. Hammer, and S.A. Stanton, *The reengineering revolution—A handbook,* HarperCollins, New York. 1995.

[13] M.Y. Cheng, and M.H. Tsai, Reengineering of construction management process, *Journal of Construction Engineering and Management*, 129(1), 2003, 105–114

[14] L. Fitzgerald, R. Johnson, S. Brignall, R. Silvestro, C. Voss, *Performance Measurement in Service Business,* CIMA, London, 1991.

[15] R. Lynch, K. Cross, *Measure Up—The Essential Guide to Measuring Business Performance,* Mandarin, London, 1991.

[16] P. Bradley, *A performance measurement approach to the reengineering of manufacturing enterprises,* Ph.D. Thesis, CIMRU, NUI Galway, Ireland, 1996.

[17] P. Folan, J. Browne, A review of performance measurement: Towards performance management, *Computers in Industry*, 56 (2005): 663–680.

[18] Z. Feng, S. Jr. Eugene, and B.L. Peter, A Performance Study on a Multi-agent E-Scheduling and Coordination Framework for Maintenance Networks, *IEEE Trans.*

Syst., Man, Cybern., Part C, Appl. Rev.,, 2007,37(1): 52-65.

[19] N. Zribi, I. Kacem, A.E. Kamel, and P. Borne, Assignment and Scheduling in Flexible Job-Shops by Hierarchical Optimization, *IEEE Trans. Syst., Man, Cybern., Part C, Appl. Rev.,* 2007,37(4): 652-661.

[20] W. Shen, S. Lang, L. Wang, iShopFloor: An Internet-Enabled Agent-Based Intelligent Shop, *IEEE Trans. Syst., Man, Cybern., Part C, Appl. Rev.,* 35(3), 371-381, 2005.

[21] W. Shen, L. Wang, Q. Hao, Agent-Based Distributed Manufacturing Process Planning and Scheduling: A State-of-the-Art Survey, *IEEE Trans. Syst., Man, Cybern., Part C, Appl. Rev.,* 36(4), 563- 577, 2006.

[22] D. Grigori, F. Casati, M. Castellanos, U. Dayal, M. Sayal, M.C. Shan. Business Process Intelligence, *Computers in Industry*, 53(2004):321-343.

[23] M. Castellanos, F. Casati, U. Dayal, M.C. Shan. A comprehensive and automated approach to intelligent business process execution analysis. *Distributed and Parallel Databases*, 16(2004):1-35.

[24] D. Amaratunga, D. Baldry, Moving from performance measurement to performance management, *Facilities,* 2002, 20 (5–6): 217–223.

[25] P. Smith, M. Goddard, Performance management and opera-research: a marriage made in heaven? *Journal of the Operational Research Society,* 2002, 53 (3): 247–255.

[26] M.R. Ostrenga, T.R. Ozan, R.D. Mcllhattan, and M.D. Harwood, *The Ernst & Young Guide to Total Cost Management,* John Wiley & Sons, New York, 1992.

[27] R.T. Yeh, and R.T. Mittermeir, A commonsense management model, *IEEE Software*, 1991,6(2): 23-33

[28] W.A. Tan, *A study and development for Dynamic Optimizing Enterprise Process Technique and its Supporting Environment,* Ph.D. Thesis, BeiHang University, BeiJing, 2001.

[29] W.A. Tan, R.B. Chen, W. Shen, J. Zhao, Q. Hao, An Agent-based Collaborative Enterprise Modeling Environment Supporting Enterprise Process Evolution, In *Computer Supported Cooperative Work in Design III*, LNCS 4402, pp. 217–226, 2007.

[30] ESPRIT Consortium AMICE. *CIMOSA: open system architecture for CIM*. Springer –Verlag, Berlin Heidelberg New York (1993)

[31] W.A. Tan, S. Li, L.G. Zeng, W. Shen, A Dynamic PERT/CPM Technique with Compound Number Supporting Enterprise Process Flexible Scheduling, In *Proceedings of the International Conference on Advanced Design and Manufacture*, January, 2006, Harbin, China, pp.197-202.

[32] W.A. Tan, B.S. Zhou, and M.S. Li.: Research on Simulation-Based Auto-Optimization Techniques in Enterprise Process Modeling. *Journal of software*, 4 (2002) 706-712.

[33] R. Kimball, *The Data Warehouse Toolkit: Practical Techniques for Building Dimensional Data Warehouse*. New York: Wiley, 1996.

[34] A. Sen and A.P. Sinha, Toward Developing Data Warehousing Process Standards: An Ontology- Based Review of Existing Methodologies, *IEEE Trans. Syst., Man, Cybern., Part C, Appl. Rev.,* 2007, 37(1):17-31.

[35] A.M. Howard, A Systematic Approach to Predict Performance of Human–Automation Systems, *IEEE Trans. Syst., Man, Cybern., Part C, Appl. Rev.,* 2007, 37(4): 594-561.

[36] J.M. Yelena, A.R. Probst, Business concepts ontology for an enterprise performance and competences monitoring, *Computers in Industry,* 58 (2007): 118–129

[37] W. Shen, D.H. Norrie, and J.P. Barthes, *Multi-Agent Systems for Concurrent Intelligent Design and Manufacturing*, Taylor & Francis, London and New York, 2001.