Performance Evaluation of Interorganizational Business Processes Based on Petri Nets

Zhiting Song*, Yanming Sun

School of Business Administration, South China University of Technology, Guangzhou, Guangdong, 510641, China

***Abstract* — Although a considerable body of literature exists on the issues of modeling and verification of interorganizational business processes (IBPs), there has been little research done to evaluate the performance of IBPs. In this paper, we presented a methodology to manage the performance of IBPs. This methodology firstly summarized a general model based on Petri nets for IBPs. According to reliability theory and graph theory, it then analyzed the performance of above model from the perspectives of structure complexity, extendibility and reliability. The proposed methodology solved the problem that formal verification cannot ensure good performance of IBPs, and facilitated the ex-ante performance-based process design and ex-post performance assessment of existing IBPs. A purchase order-fulfillment process in the supply chain of collaborative manufacturing was used to illustrate this methodology.**

Keywords - Interorganizational business processes; Performance evaluation; Petri nets

I. INTRODUCTION

With the unceasing development of economic globalization and informationization level, business models of enterprises change dramatically, that is, business activities of enterprises have transformed from single-objective and independent modes to multi-objective and cooperative modes [1]. According to CCW Research at the beginning of 2014, 73% of the manufacturing enterprises in China cooperated with their suppliers, distributors, and partners through systems of enterprise resource planning (ERP), supply chain management (SCM) and customer relationship management (CRM) to share data, which shows that business process significantly spans organizational boundaries. Summary report in 2015, which is concluded from 200 enterprises that first pass the certification of Chinese management systems for integration of informationization and industrialization, reveals that business process cooperation is a crucial way for enterprises to keep sustainable competitive advantage and cultivate new competitiveness.

Recently, research on IBPs becomes a focus in business process literature. Aalst is a pioneer of inter-organizational workflow modeling [2-7]. He originally establishes inter-organizational workflow net (IOWF-net) by applying communication elements to connect local workflows, and verifies the soundness of IOWF-net [2]; then Aalst uses message sequence charts (MSC) to indicate the structures of communication elements and conducts soundness and consistency verifications [3, 4]; based on projection inheritance, he proposes a public-to-private (P2P) approach to model inter-organizational workflow and analyzes the properties of safeness and soundness [5, 6]; recently, he models inter-organizational processes via open workflow nets (oWFNs) which defines the processes from both public and private views, and verifies the consistency of the processes under the two views [7]. To distinguish different organizational workflows, Cui et al. [8] present a colored inter-organizational workflow model (C-IOWF) to depict inter-organizational workflow, and study its soundness. Grefen et al. [9] propose a three-level framework for dynamic service outsourcing, which roughly specifies the relations of the processes in an organization and between two organizations; based on the above framework, Norta [10] constructs Petri nets-based models for dynamic IBPs, which utilizes Petri nets to model processes at all levels, explores the mapping relations among the three processes via projection inheritance, and connects processes in different organizations by interfaces. Ge et al. [11] explain inter-organizational workflows through interaction-oriented Petri net (IPON) which employs WF-net to model private processes in organizations and denotes cooperation between organizations by interactions between transitions in different workflows, and present relaxed soundness to verify the correctness of IPON. Li et al. [12] employ service workflow net (SWFN) to model each Web service process which is connected via communication places, and develop an approach called communication reachability trees for correctness verification. Wang et al. [13] extract public views from private processes, assemble public views into global communication structure, establish interactive relations between communication structure and each private process, and finally build Petri nets-based models for inter-organizational workflows. Zeng et al. [14] define the OTRM-net by extending Petri nets with task elements including execution organization, resource cost and message etc., which formally models the task coordination patterns and disposal processes in emergency response systems. Mo et al. [15] divide collaborative processes into several parallel modules which constitute an IBP. In conclusion, research on IBPs mainly concentrates in formal modeling and verification, of which the former establishes models for IBPs via using Petri nets to describe processes of organizations and the complex interactions among them [2-15], while the latter verifies properties such as soundness and consistency for the established models [2-4, 6-8, 11, 12].

As applications of IBP expand and deepen, the overall scale of IBP increases considerably and its structure affects the realization of process function to a larger degree. Process design in terms of formal verification only enables IPBs to behave correctly and consistently during their implementation, but cannot ensure good structural properties of IBPs which cover performance of structure complexity, extendibility and reliability. Performance evaluation is a key activity in IBP management for it provides theoretical bases to design, implement, maintain and transform IBPs, yet seldom have researchers studied it.

Therefore, the paper researched the performance of IBPs based on literature [16]. First, this paper established a general Petri nets-based model for IBPs, then proposed specific quantitative formulations for performance, and ultimately conducted a case study. Compared with existing research, our work fills in the gaps that formal verification guides process design and management practically, which is crucial for IBPs to benign good performance.

II. MODELING IBPS

Most of existing research directly integrates sub-processes into an IBP based on fusion of communication places or process concurrency [2-14], which is a basis for us to develop a general model for IBPs. This paper adopted the formal definitions of WF-net from Aalst [17] to describe the general model.

Definition 1[17] A Petri net $PN = (P, T, F)$ is a workflow net (WF-net) if and only if:

(1) PN has two special places: i and o. Place i is a source place: $\cdot i = \varnothing$. Place o is a sink place: $o\cdot = \varnothing$.

(2) If a transition t^* is added to PN to connect place i with o (i.e. $\cdot t^* = \{o\}$ and $t^*\cdot = \{i\}$), the resultant Petri net is strongly connected.

Definition 2 The general model for IBPs is a tuple $H_0 = (p^i, t^i, p^o, t^o, BP, P_c, F_c)$, where:

(1) Places p^i and p^o denote the starting and ending places of H_0: $\cdot(p^i) = \varnothing \wedge (p^i)\cdot = t^i$, $\cdot(p^o) = t^o \wedge (p^o)\cdot = \varnothing$.

(2) Transitions t^i and t^o are the starting and ending transitions of H_0: $\cdot(t^i) = p^i \wedge (t^i)\cdot = \{i_1, i_2, \ldots, i_k\}$, $\cdot(t^o) = \{o_1, o_2, \ldots, o_k\} \wedge (t^o)\cdot = p^o$. Places i_j and o_j are the starting and ending places of sub-process bp_j $(j \le k)$.

(3) $BP = \{bp_1, bp_2, \ldots, bp_k\}$ is a nonempty and finite set of sub-processes, of which bp_j $(j \le k)$ is a WF-net.

(4) P_c is a finite set of communication places. If $P_c \neq \varnothing$, $\forall p_c \in P_c$, $\cdot(p_c) = t_m \wedge (p_c)\cdot = t_n \wedge t_m \in bp_i \wedge t_n \in bp_j \wedge i \le k \wedge j \le k \wedge i \neq j$ holds.

(5) F_c is a finite and nonempty set of arcs. $F_c = (p^i, t^i) \cup \{(t^i, i_j)|i_j \in bp_j, j \le k\} \cup \{(o_j, t^o)|o_j \in bp_j, j \le k\} \cup (t^o, p^o) \cup \{(t_m, p_c), (p_c, t_n)|p_c \in P_c \wedge t_m \in \{\cdot(p_c)\} \wedge t_n \in \{(p_c)\cdot\}\}$ if $P_c \neq \varnothing$. Otherwise, $F_c = (p^i, t^i) \cup \{(t^i, i_j)|i_j \in bp_j, j \le k\} \cup \{(o_j, t^o)|o_j \in bp_j, j \le k\} \cup (t^o, p^o)$.

Transitions in H_0 represent tasks while places denote dependency relations among tasks. A place contains zero or more tokens at any time, and tokens represent data units. Tokens flow along the paths leading from i to o, which denotes the completion of a business. Definitions 1 and 2 not only enable us to model IBPs formally, but also provide the essential elements for mathematical formulations of performance.

III. MODELING PERFORMANCE OF IBPS

An IBP utilizes computer network technology to coordinate resources of human, equipment and data of different organizations to fulfill tasks in a specified sequence [18], and its model defined above simulates the relations between data and tasks which are supported by equipment. Therefore, performance of an IBP reflected by its Petri nets-based model is influenced by equipment, data and tasks as well as their relations. This section analyzes performance including structure complexity, extendibility and reliability, of which the former two are affected by data and tasks as well as their relations while reliability is still influenced by equipment.

A. Modeling Structure Complexity

The aim to study structure complexity is to know the element, structure, state and procedure of an IBP, of which the former two reflect its static structure features while the latter two describe the dynamic behavior features.

Let C_n and C_r be the element complexity and relevance complexity of IBPs. C_n captures the quantitative characteristics of data and tasks in IBPs and makes participants get a general knowledge of business-fulfillment process, while C_r describes the relevance characteristics between data and tasks, and enables participants to gain insight into occupation and transformation of data and execution conditions of tasks. The structure complexity of IBPs, denoted as C_s, assesses the element complexity and relevance complexity comprehensively.

When using Petri nets to model IBPs, C_n is a function of the quantity of places and transitions:

$$C_n = \frac{1}{2}\left(\frac{|P| - 1}{|P|} + \frac{|T| - 1}{|T|}\right) = 1 - \frac{1}{2m} - \frac{1}{2n}, \quad (1)$$

where $|P| = m$, $|T| = n$.

In Petri nets, conflict problems emerge once the postset of place p_i contains two or more transitions (i.e. $\left|p_i^{\cdot}\right| \geq 2$).**Error! Reference source not found.**Conflict problems arise in IBPs if tasks compete for the same data (i.e. executive authority), which causes indefinite behaviors of IBPs, makes data control complicated, and then adds structure complexity. Thus, we analyze relevance complexity for the configuration, generation and usage of data. The relevance complexity of place p_i is:

$$c_{pi} = \frac{\left|p_i^{\cdot}\right|}{\left|{}^{\cdot}p_i\right| + \left|p_i^{\cdot}\right|}, \quad (2)$$

where ${}^{\cdot}p_i$ **Error! Reference source not found.**and $p_i^{\cdot}$ **Error! Reference source not found.**represent the preset and postset of p_i. c_{pi} measures the ability of place p_i to output data. For example, the storage place of order information transits two copies of inerrant order information to its downstream for checking payment information and contract information. The relevance complexity for the set of places (i.e. P) is:

$$C_P = \frac{1}{|P|}\sum_{i=1}^{|P|}\frac{\left|p_i^{\cdot}\right|}{\left|{}^{\cdot}p_i\right| + \left|p_i^{\cdot}\right|} = \frac{1}{m}\sum_{i=1}^{m}\frac{\left|p_i^{\cdot}\right|}{\left|{}^{\cdot}p_i\right| + \left|p_i^{\cdot}\right|}. \quad (3)$$

Similarly, the more the preset of transition t_i contains, the more the data is involved, and the more easily deadlocks occur, which makes task control complicated and adds structure complexity. The relevance complexity for the set of transitions (i.e. T) is:

$$C_T = \frac{1}{|T|}\sum_{i=1}^{|T|}\frac{\left|{}^{\cdot}t_i\right|}{\left|{}^{\cdot}t_i\right| + \left|t_i^{\cdot}\right|} = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|{}^{\cdot}t_i\right|}{\left|{}^{\cdot}t_i\right| + \left|t_i^{\cdot}\right|}, \quad (4)$$

where ${}^{\cdot}t_i$ **Error! Reference source not found.**and $t_i^{\cdot}$ **Error! Reference source not found.**signify the preset and postset of transition t_i. C_T captures the ability of tasks to consume data resource. For example, the task to arrange production launches after receiving payment information and contract information.

The relevance complexity of an IBP is defined as the mean of C_P and C_T:

$$C_r = \frac{C_P + C_T}{2}. \quad (5)$$

When $C_r < 0.5$, the relevance structure of an IBP is simple; when $C_r = 0.5$, the relevance structure is idle; when $C_r > 0.5$, the relevance structure is complex.

As C_n and C_r exert different influence on C_s, let λ be the correlation coefficient between C_n and C_s. Thus, C_s is defined as:

$$C_s = \lambda C_n + (1 - \lambda)C_r. \quad (6)$$

In the Petri nets-based models of IBPs, nodes are elements that constitute IBPs. The effect that nodes exert on structure complexity, denoted as λ, is determined by the ratio between the sum of the preset and postset of nodes and the number of arcs, and the mathematical expression of λ is:

$$\lambda = \frac{1}{|P| + |T|}\sum_{i=1}^{|P|+|T|}\frac{\left|{}^{\cdot}x_i\right| + \left|x_i^{\cdot}\right|}{|F|}, x_i \in X, \quad (7)$$

where X denotes the set of nodes that have nonempty preset and postset, and F is the set of direct arcs in the net.

B. Modeling Extendibility

Extendable function, a precondition for an IBP to suffer from dynamic scenarios, can be achieved through extendable structure because function and structure are correlated. Relations among nodes of IBPs determine process structure so that there is a need to analyze those relations. The relations between one node and the others denote its impact on IBPs, which can be measured by coupling intensity.

Definition 3 For $x_i \in H_0$, if ${}^{\cdot}x_i \neq \varnothing \wedge x_i^{\cdot} \neq \varnothing$ **Error! Reference source not found.**holds, the coupling intensity of node x_i is:

$$d(x_i) = \frac{1}{2}\left(\frac{|Mx_i|}{M_s} + \frac{|R_{max}(x_i)|}{|X|}\right), \quad (8)$$

where Mx_i is the set of meshes that are correlated with x_i, M_s is the total number of meshes, and $R_{max}(x_i) = max\left(\begin{matrix}\{\forall y | y \in x_i \vee y \in x_i\}, \\ \{\forall y | y \in m_e \wedge m_e \in Mx_i \wedge m_e = max(Mx_i), y \neq x_i\}\end{matrix}\right)$.

Coupling intensity of a node measures its weight in IBPs. Generally, actions on nodes with greater coupling intensity impact more heavily on process function, and maintenance and expansion of those nodes are more difficult, and vice versa. If process structures must be adjusted, we should first adjust the nodes with small coupling intensity, followed by the nodes with medium coupling intensity and the nodes with great coupling intensity.

Definition 4 The average coupling intensity is denoted as $D = \frac{1}{|X|}\sum_{i=1}^{|X|} d(x_i)$ **Error! Reference source not found.**, and node x_j is a key node if $d(x_j) > D$**Error! Reference source not found.** holds.

Let V_k be the set of key nodes. The more elements V_k contains, the more complex the relations are among nodes, and the more difficult it is to transform and extend IBPs, and vice versa.

C. Modeling Reliability

Definition 5 $G = (V, E)$ is a connected undirected graph with weighted vertexes. Let $R(G) = (V(G_r), E(G_r))$ be the core subgraph of G if and only if: V_k is the set of key vertexes with V_k □ V, $E(G_r) = \{e_i | e_i$ is incident with $v_j \wedge v_j \in V_k \wedge e_i \in E\}$, and $V(G_r) = \{v_i | v_i \in V_k \vee v_i$ is incident with $e_j \wedge e_j \in E(G_r)\}$.

Definition 6 Let $h(G) = \max\{\omega(G - \delta_i) - |E(\delta_i)|$ $\delta_i \in C(G)$, R_G □ $\delta_i\, (i = 1, 2, \ldots, n)\}$ be the weighted core degree of G ($|V| \geq 4$), where δ_i is a graph that divides graph $G - \delta_i$ into two or more connected branches, $C(G) = \{\delta_1, \delta_2, \ldots, \delta_n\}$, $\omega(G - \delta_i)$ denotes the number of the connected branches in $G - \delta_i$, and $E|\delta_i|$ signifies the number of the edges in δ_i. δ^* is the weighted core of G if $\omega(G - \delta^*) - E|\delta^*| = h(G)$ holds.

H_0 defined above can be mapped into two graphs that satisfy definition 5, denoted as G_t and G_p. G_t, with weighted transitions, reflects the relations among tasks in IBPs. G_p, with weighted places, describes the data resource configuration. The two graphs are equally important to describe process behaviors. Thus, G_t and G_p codetermine the weighted core degree and weighted core of H_0.

Definition 7 The weighted core degree $h(H_0)$ and weighted core $\delta^*(H_0)$ of H_0 are denoted as $h(H_0) = h(G_t) + h(G_p)$ and $\delta^*(H_0) = \delta^*(G_t) \cup \delta^*(G_p)$, where $h(G_t)$ ($h(G_p)$) and $\delta^*(G_t)$ ($\delta^*(G_p)$) denote the weighted core degree and weighted core of G_t (G_p).

$\delta^*(H_0)$, the core layer of H_0, is also denoted as H_1. If H_1 is connected, we can extract a core layer from H_1, denoted as $H_2 = \delta^*(H_1)$. By that analogy, a pyramidal structure, H_0, H_1, H_2, …, H_n, forms and satisfies H_0 □ H_1 □ H_2 □ … □ H_n. The higher the core layer is, the more important it is. During the design and implementation phases of IBPs, we should give different treatments to each core layer according to its importance respectively. For example, performance requirements of equipment in H_n take top priority; as to H_0, we can adopt economic means to meet that requirements. Hierarchical partition facilities not only the design of IBPs, but also the reliability assessment and improvement of IBPs.

Enterprise collaboration relies heavily on the overall quality of an IBP which can be measured by
reliability of the IBP. An IBP includes multiple nodes, so its reliability is determined by the reliability of all nodes. In series and parallel processes, the relations between process reliability $R_s(t)$ and node reliability ($R_i(t)$, $i = 1, 2, \ldots, n$) are:

$$R_s(t) = \prod_{i=1}^{n} R_i(t), \tag{9}$$

$$R_s(t) = 1 - \prod_{i=1}^{n} \left(1 - R_i(t)\right). \tag{10}$$

Node function is accomplished by equipment whose reliability is assumed as a constant $R(t)$. Redundancy generally refers to dual redundancy, putting two identical equipment in parallel for a node. After dual redundancy, node reliability is:

$$R_s(t) = 1 - \left(1 - R(t)\right)^2 = 2R(t) - R^2(t). \tag{11}$$

Let I_j ($j = 0, 1, \ldots, m$) denote the weight of nodes in H_j, where $I_j = j + 1$, so the total weight of all nodes is:

$$I_s = \sum_{j=0}^{m} I_j \left|H_j - H_{j+1}\right|, \tag{12}$$

where $H_j - H_{j+1}$ denotes the nodes that inside H_j and outside H_{j+1}, the proportion of reliability of H_j is:

$$K_j = \frac{I_j \left|H_j - H_{j+1}\right|}{I_s} \times 100\%. \tag{13}$$

Each layer is connected, and the nodes in H_i are independent of the nodes in H_j, where $i \neq j$. Suppose that the reliability of H_j is $R_j(t)$, then process reliability is:

$$R_s(t) = \sum_{j=0}^{m} R_j(t) K_j. \tag{14}$$

Without redundancy, we express the reliability of H_j as $R_j(t) = \left(R(t)\right)^{\left|H_j - H_{j+1}\right|}$ **Error! Reference source not found.**according to Eq. (9), and the process reliability in this case is:

$$R_s(t) = \sum_{j=0}^{m} \left(R(t)\right)^{\left|H_j - H_{j+1}\right|} K_j. \tag{15}$$

Similarly, according to Eq. (11), the process reliability under dual redundancy is:

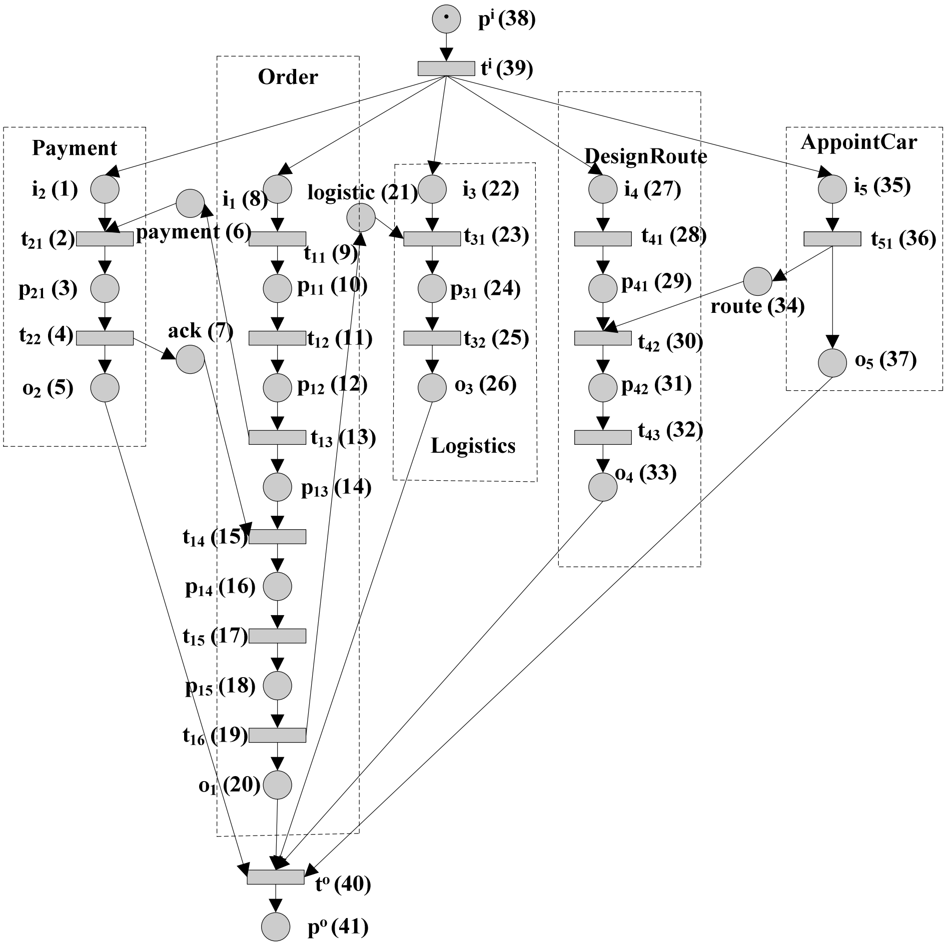


Fig.1 An example of IBP

$$R_s(t) = \sum_{j=0}^{m} \left(2R(t) - R^2(t)\right)^{\left|H_j - H_{j+1}\right|} K_j \, . \qquad (16)$$

In line with Eq. (15) and Eq. (16), we can conclude that reducing the number of the nodes in high layers is an effective way to improve reliability.

IV. CASE STUDY

This section discusses the implementation of our methodology using the example of figure 5 in literature [15], denoted as Fig. (**1**). We use it as an example because its establishment is based on fusion of communication places and process concurrency. Fig. (**1**) shows a purchase order-fulfillment process in the supply chain of collaborative manufacturing. The IBP includes 5 sub-processes of AppointCar, DesignRoute, Logistics, Payment and Order, each of which belongs to an enterprise.

A. Analysis of Structure Complexity

Based on related equations, we work out the values of C_n, C_P, C_T, C_r, λ and C_s, as shown in Table I.

Table I shows that C_r accounts for the vast majority proportion of C_s, which implies that reducing relevance complexity C_r is effective to simplify the structures of IBPs.

B. Analysis of Extendibility

It is difficult to find out all the meshes of Fig. (**1**) artificially, so we adopt DFS algorithm written in Java to achieve this goal. Results show that the number of the meshes is 92, and the other parameter values for all nodes are shown in Fig. (**2**).

As shown in Fig. (**2**), the average coupling intensity D equals 0.571, and the set of key nodes is V_k = {2, 3, 4, 6, 7, 13, 15, 16, 17, 18, 19, 21, 23, 30, 36, 39, 40}. Notably, nodes 2, 4, 13, 15, 19, 23, 30 and 36 have stronger coupling intensity than other key nodes, for these key nodes offer service to two or more organizations. For key nodes, especially those providing service to multiple organizations, we should give significant investment and preferential configuration and reduce or even avoid modification, which is important to the normal operation of IBP.

TABLE I. DETAILS OF STRUCTURE COMPLEXITY

C_n	C_P	C_T	C_r	λ	C_s
0.949	0.5	0.5	0.5	0.048	0.522

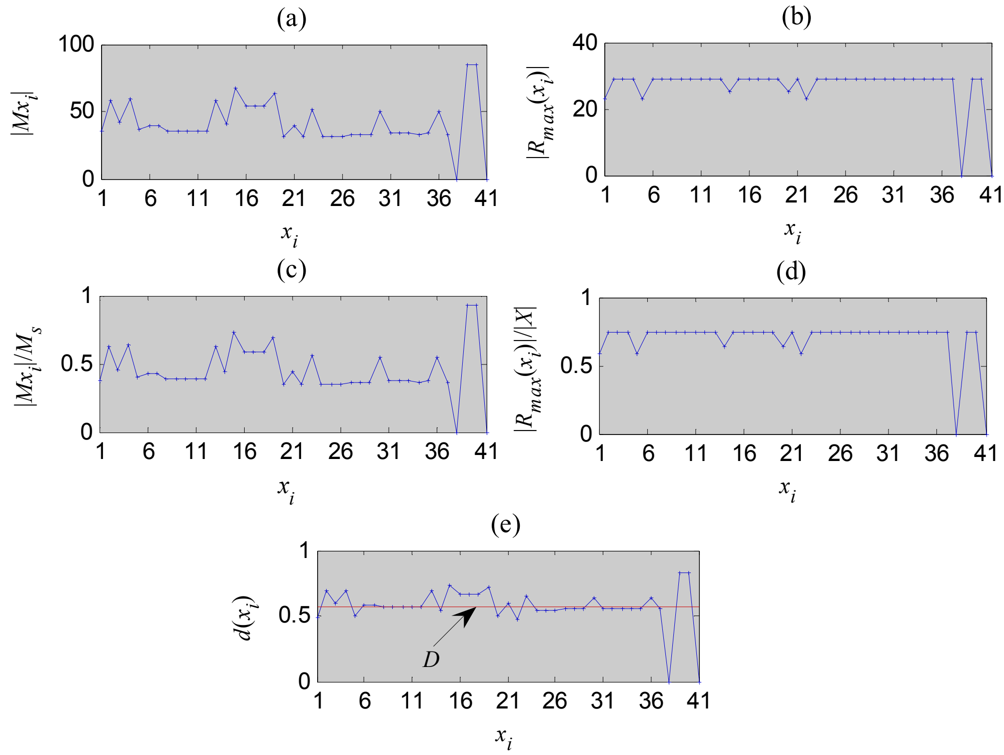
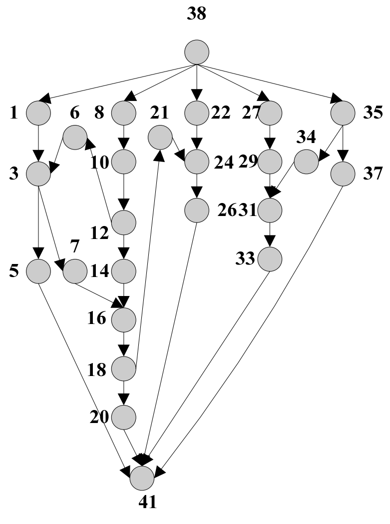


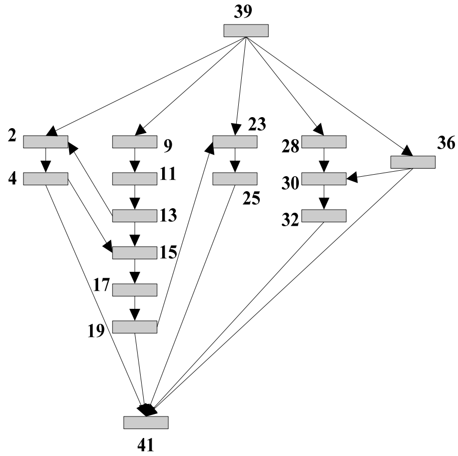
Fig.2 The Values of $|Mx_i|$, $|R_{max}(x_i)|$, $|Mx_i|/M_s$, $R_{max}(x_i)/|X|$ and $d(x_i)$ for all nodes

C. Analysis of Reliability

According to literature [16], Fig. (**1**) can be converted into two directed graphs, denoted as D_t and D_p. Fig. (**3**) presents the structures of them.



(a) D_p

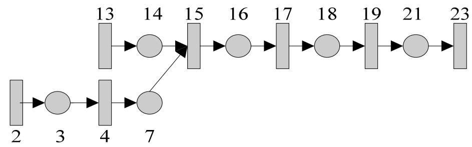


(b) D_t
Fig.3 The structures of D_p and D_t

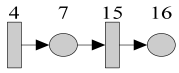
G_p and G_t are undirected graphs corresponding to D_p and D_t separately. The weighted core degrees and weighted cores of G_p and G_t are: $h(G_t) = -5$, $\delta^*(G_t) = (\{2, 4, 13, 15, 17, 19, 23\}, \{(2, 4), (4, 15), (13, 15), (15, 17), (17, 19), (19, 23)\}$; $h(G_p) = -4$, $\delta^*(G_p) = (\{3, 7, 14, 16, 18, 21\}, \{(3, 7), (7, 16), (14, 16), (16, 18), (18, 21)\})$.

According to definition 7, the weighted core degree and weighted core of Fig. (1) are calculated as: $h(H_0) = h(G_t) + h(G_p) = -5 - 4 = -9$, $H_1 = \delta^*(H_0) = \delta^*(G_t) \cup \delta^*(G_p) = (\{2, 4, 13, 15, 17, 19, 23, 3, 7, 14, 16, 18, 21\}, \{(2, 4), (4, 15), (13, 15), (15, 17), (17, 19), (19, 23), (3, 7), (7, 16), (14, 16), (16,18), (18, 21)\})$.

Fig. 4(**a**) is the core layer that $H_1 = \delta^*(H_0)$ describes, and the core layer of H_1, denoted as H_2, is shown in Fig. 4(**b**).



(a)H_1



(b)H_2
Fig.4 Core layers at all levels of Fig.1

To sum up, we can part Fig. (**1**) into three layers of H_0, H_1 and H_2. Table II lists the values of parameters K_j, I_j and $|H_j - H_{j+1}|$for layer H_j (j = 0, 1, 2).

TABLE II. THE VALUES OF $|H_J - H_{J+1}|$, I_J AND K_J FOR ALL LAYERS

Layer	H_0	H_1	H_2
$\|H_j - H_{j+1}\|$	28	9	4
I_j	1	2	3
K_j	0.48	0.31	0.21

According to Eq. (15) and Eq. (16), parameters in Table II influence both the redundancy programs and the reliability under each program. Thus, we offer a detailed analysis of the redundancy programs about Fig. (**1**) based on the principle that redundancy starts from equipment at the innermost layer and turns to peripheral equipment layer by layer.

Let node reliability equal 98% when it running alone, denoted as $R(t)$ = 98%. Based on Table II, different redundancy programs are designed for corresponding layers, and the comparisons among different redundancy programs are shown in Table III.

TABLE III. COMPARISONS AMONG DIFFERENT REDUNDANCY PROGRAMS

Redundancy program	Equipment needed	Reliability R_s	Program comparison	Percentage Increment in the equipment (%)	Percentage Increment in the R_s (%)
① No redundancy	41	72.5%			
②Full redundancy	82	99.3%	②: ①	100%	37.0%
③ Redundancy of H_2	54	79.1%	③: ①	31.7%	9.1%
			③: ②	-34.1%	-20.3%
④ Redundancy of H_1	45	74.1%	④: ①	9.8%	2.2%
			④: ②	-45.1%	-25.4%
			④: ③	-16.7%	-6.3%

As stated in Table III, the priorities of redundancy programs are ②, ③ and ④ if we only seek for high reliability; if equipment is unavailable, the priorities are ④, ③ and ②; if we have to consider both reliability and equipment, the satisfactory solution is ④; if conditions permit, the optimal program is ②.

Reliability analysis indicates that factors of node reliability, core layers and redundancy degree all influence reliability. Therefore, in the design phase of IBPs, we should first work out the preliminary process based on practical requirements on function and performance, then analyze and improve reliability layer by layer to satisfy constraints of reliability and cost.

V. CONCLUSIONS

To ensure good structures of IBPs, the paper proposed a methodology to analyze their performance. This methodology firstly established a general Petri nets-based model for IBPs and discussed structure complexity and extendibility of IBPs based on the established model, and then mapped the model into two graphs to explore core layers and reliability of IBPs, finally illustrated the methodology through a purchase order-fulfillment process in the supply chain of collaborative manufacturing. Results show that performance evaluation fills the gaps in IBP literature and facilitates realization of process function and optimization of process structure in practice. Future work includes improving process performance and optimizing robustness of IBPs.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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