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A framework for Industrial Product–Service Systems risk management

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Abstract

With the fast development of service economy, researches and applications of Industrial Product–Service Systems have become popular. Advantages and benefits of Industrial Product–Service Systems are widely discussed, while risks and uncertainties resulting from this transformation tide are rarely investigated. There are strong appeals from the industry for a holistic Industrial Product–Service Systems risk management architecture. Based on a full review on the existing work, an Industrial Product–Service Systems risk management framework integrating multiple methods is proposed trying to provide a possible solution. Structure–process correlation analysis is used for Industrial Product–Service Systems modeling. Risk recognition matrix and graphic risk units integrating with dynamic Bayesian network are developed for risk recognition and modeling. Entropy reduction value–based and effect chains' visualized analysis offer an efficient approach for key risk and key node recognition. The proposed methods get tested and verified with a case study of risk management for hydraulic system maintenance service in excavator Industrial Product–Service Systems.

Keywords

Industrial Product–Service System, risk management, dynamic Bayesian network, entropy reduction value, risk analysis

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Introduction

With resource conservation, environmental protection, user experience, lower costs and waste reduction have become the basic notions of the 21st-century economy; traditional simple product manufacturing and transaction modes are no longer going to meet the development requirements of the new epoch. Then, the concept of Industrial Product–Service Systems (IPS2) was proposed, aiming to coordinate the interests of environment, manufacturers, service providers, customers and other participating stakeholders and pursuit the idea of contradiction elimination and value co-creation.

The updated business modes disrupted the original relatively stable relationships, so the structure and connections of the operational systems need to be rebuilt. Meanwhile, because of more long-term cooperation and complex relationships, both chances and risks have to be redefined and reevaluated. While chances and benefits of IPS2 have been studied a lot, little attention has been paid to their negative sides, namely, operational risks of IPS2. IPS2 risk factors, mechanisms and possible consequences still need to be studied, not to mention an overall risk management architecture for IPS2. These problems will seriously hinder the further development of business modes based on IPS2.

In order to fill the gap, the authors try to figure out an executable framework for IPS2 risk management. Moreover, the corresponding supporting tools and methods also need to be developed for specific problem solving, especially for IPS2 modeling, as well as risk modeling and analysis. That will need systematic works from an overall perspective. According to this train of thought, we launched a series of research. Works and findings of our research in this article will be organized as follows.

First, the background for IPS2 risk management is analyzed and a literature review about the common methods for risk management in other areas is given,

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Table 1. IPS2 motivations and risk implications' analysis.

Motivations	Cases	Risk implications
Enabler of sustainable consumption	Lease service of household appliances and private cars	Less production wastes, but more energy and resource consumption
Improved control over supply chain	Maintenance for construction equipment, aero engine	Less risks for users and operators, but improved risks for MROs
Less capital expenditure	Public facilities: schools, transport infrastructure, etc.	Less capital expenditure, but lower quality for seeking profit for OEMs
Slowdown in the demand for products	Military procurement, construction equipment lease	Less product demands, but more product inventory and slower turnover of capital

MRO: maintenance, repair and overhaul provider; OEM: original equipment manufacturer.

highlighting the advantages of dynamic Bayesian network (DBN) in IPS2 risk modeling. Then, a specialized integral framework for IPS2 risk management is proposed. After that, methods for IPS2 modeling are developed, including contexts establishing and IPS2 modeling-based structure–process correlation analysis. Next, DBN-based IPS2 risk recognition, modeling and assessment methods and tools are developed. Then follows a case study of excavator IPS2 risk management of hydraulic maintenance system failure in construction machinery industry.

Background and literature review

IPS2 and their risks

IPS2 was developed based on the concept of Product–Service Systems (PSS), which is defined as the combination of tangible products and intangible services in a market that can fulfill consumers' needs and a result of rethinking of the product value chain and ways of delivering utility to customers that will have a smaller environmental impact than separate products and services outside the system.[1–3] It was proposed as a means to reach sustainable consumption and described as an incorporated paradigm shift from leadership in technology to leadership in use which enables innovative business models.[4] Apart from this, there are also many more other motivations that apply. A comparison of different IPS2 motivations is conducted as shown in Table 1.

Environmental and economic advantages of IPS2 have been studied a lot.[5–7] But every medal has its reverse. Beyond all the advantages and positive sides of IPS2 mentioned above, the dynamic characters, risks and uncertainties of IPS2 gradually appealed the attention of researchers recently. Hidden risks are associated with servitization and there is a greater proportion of bankrupt servitized firms than would be expected.[8] As analyzed in Table 1, different motivations may have different risk implications to the system. Some other researchers also tried to interpret these phenomena. Ng and Yip[9] tried to identify IPS2 risks and their impact on contracting by a case of the defense industry. Herzog et al.[10] researched the nature of risk management in the early phase of IPS2 design. Maiwald et al.[11] derive propositions about inherent characteristics of IPS2 provision that increase customers' perceived risk—customers' need uncertainty, challenges of evaluating IPS2 performance, change processes triggered by IPS2 implementations and entering long-term relationships.

Based on different workflow and relationship, IPS2 can be summarized as three different business modes: product-oriented IPS2, use-oriented IPS2 and performance-oriented IPS2.[12–15] They have different focal points of risk management as shown in Table 2.

As shown in Table 2, as IPS2 evolve from product-oriented IPS2 to performance-oriented IPS2, risks transfer gradually to suppliers,[9] which is believed to be the root cause of IPS2 risks. IPS2 come up with a new way to allocate the risks, also considering the incentives of the different actors.[16] Different from traditional business models, under IPS2 circumstances, in order to increase opportunities, product and service providers have to take over the risks originally burdened by customers. Meanwhile, disperse risk management modes have to change to centralized management modes.

No doubt, the analysis, assessment and management of IPS2 risks have significant meanings for further development. Though works mentioned above have tried to analyze the sources of IPS2 risks from a qualitative and logic view, none of them has proposed an effective framework and operable methods for quantitative assessment of IPS2 risks.

Methods for system risk analysis

Lots of tools and methods for system risk management have been proposed, among which failure mode and effect analysis (FMEA), analytical hierarchy process (AHP), fault tree, Petri nets and BNs are the commonly used ones for risk analysis and management.

FMEA was first proposed for analysis and design of aircraft operating system. But now it is developed and widely applied to all kinds of areas, for example, mechanical system diagnosis, project risk management and microelectronics reliability.[17–19] But FMEA has been found to have limited validity when used in

Table 2. Focal points of different IPS2 business modes.

Business modes	IPS2 characters	Focal point of risk management
Product-oriented IPS2	Simple transaction relationship Users own products and usufruct Service for integrity Users pay for products and extra service	Users take the major risks for sunk costs of fixed assets occupation and cash investments, also the loss and opportunity costs due to the unavailability and inutility of products
Use-oriented IPS2	Leasehold relationship Providers possess products Users have usufruct Service for availability and utility Users pay for the service	Suppliers take the risk for sunk costs of fixed assets occupation and cash investments, while users take the loss and opportunity costs due to the unavailability and inutility of products
Performance-oriented IPS2	Cooperation relationship Providers possess products Users have the beneficial rights Service for the efficacy and results Users pay for the service	Suppliers take both the major risks for sunk costs of fixed assets occupation and cash investments, also the loss and opportunity costs due to the unavailability and inutility of products

IPS2: Industrial Product–Service Systems; OEM: original equipment manufacturer.Suppliers can be OEMs, retailors, service providers and so on.

isolation, because of the challenges around scoping and organizational boundaries.[20]

AHP is a simple, flexible and practical multi-criteria decision-making approach to the quantitative analysis of qualitative problem, which integrates expert opinions and objective judgment results and sequence factors by calculation of their relative weight. Risk management is one of its main application areas.[21–23] While the method is technically valid and practically useful, it is criticized because of the phenomenon called rank reversal.[24]

Fault tree is a top–down, deductive failure analysis method, described as a special kind of inverted tree logical causality diagram, widely used in risk problem modeling,[25] system fault diagnostics,[26] software reliability engineering[27] and so on. Fault tree is good at showing how resistant a system is to single or multiple initiating faults, but not good at finding all possible initiating faults.

Petri nets is a kind mathematical modeling language for the description of distributed systems. Vernez et al.[28] and lots of other researchers developed and used Petri nets for system risk analysis and accident modeling. But Petri nets have limitations in modeling large-scale model and those problems relating to the change in time.

But when we come to the problem of IPS2 risk modeling and analysis, special characters of IPS2 should be taken into account. Because of wide participation of humans, IPS2 is more a social or organizational system than a lifeless mechanical, electronic or software system. Uncertainty of customer needs, change in government policies and fluctuation of provisions, any of them could lead to IPS2 operational risks. The complexity and dynamic features of IPS2 call for a suitable solution. In recent years, risk modeling and analysis with BNs in the area of biological system, social systems and organization has appealed researchers' great attention.

Iung et al.[29] developed a methodology for probabilistic risk analysis of socio-technical systems integrating system knowledge structuring and unified modeling by means of BN. Hamilton et al.[30] applied BN to model the risk of *Lyngbya majuscula* bloom initiation in Deception Bay, Queensland, Australia. In addition, cases of risk factors modeling in maritime transportation,[29] offshore safety,[31] nuclear waste disposal,[32] Hurricane evacuation[33] and so on were reported.

Weber et al.[34] made a detailed review about application of BNs to dependability, risk analysis and maintenance from 1990 to 2008 and compared BN with fault trees, Markov chains and other methods. With a lot of methodological and applicative research, BN is proved to be a useful formalism in the risk analysis domain due to their ability to model probabilistic data with dependencies between events.

The Bayesian statistical approach allows to integrate different sources of information coming from failure data collection, self-assessment, industry operation data and opinion of risk managers, to give a unified knowledge for risk analysis. That allows to combine backward-looking historical data with forward-looking expectations and opinions and, at the same time, through BNs we can also consider the correlation between losses of different business lines and risk types and can evaluate the impact of causal factors.

The authors' research group is dedicated on several IPS2 projects, which include elevator, civil aircraft and construction machine (CM). Products in these industries are becoming much more intelligent. Data and information can be obtained, stored and transferred to service providers in real time. Our cooperative enterprises all have built advanced information service platforms and kept recording data for more than 10 years. In addition, cloud computing and big data analytics have been developed to improve the data acquisition, storage and analysis techniques a lot. Moreover, risks in those IPS2 of the three industries are related to public safety. Because of that, it is the responsibility of every stakeholders involved in the IPS2, including public bodies, to share their information to those OEMs

and service providers. And government departments do have some public information service platforms to support the development of IPS2 in these industries. So, the access of data source is much better than expected. This offers the very good foundation for the application of DBN in IPS2 risk management.

DBN

A BN is a directed acyclic graph in which every node represents a random variable with a discrete or continuous state.[35,36] The relationships between variables, pointed out by arcs, are interpreted in terms of conditional probabilities according to Bayes theorem.

With the BN is implemented the concept of conditional independence that allows the factorization of the joint probability, through the Markov property, in a series of local terms that describe the relationships between the variables

$$f(x_1, x_2, \ldots, x_n) = \prod_{i=1}^{n} f(x_i|pa(x_i)) \tag{1}$$

where $pa(x_i)$ denotes the states of the predecessors (parents) of the variable X_i (child).[35–37]

DBN was developed based on BN, taking the time factor into account. A DBN is still a BN, but further relates variables to each other over adjacent time steps. DBN is often called a Two-Timeslice BN because at any point in time T, network parameters can be calculated from the internal regressors and the immediate prior value (time $T-1$). DBNs have shown potential for a wide range of data mining applications by integrating priori and posterior knowledge.[36]

The initial knowledge is represented in the form of a prior probability distribution over model structures and parameters and updated using the data to obtain a posterior probability distribution over models and parameters. More formally, assuming a prior distribution over model structure $P(M)$ and a prior distribution over parameters for each model structure $P(\theta(M)$, a data set D is used to form a posterior distribution over models using Bayes rules

$$P(M|D) = \frac{\int P(D|\theta, M)P(\theta|M)d\theta P(M)}{P(D)} \tag{2}$$

which integrates the uncertainty in the parameters. For a given model structure, we can compute the posterior distribution over the parameters

$$P(\theta|M, D) = \frac{P(D|\theta, M)P(\theta|M)}{P(D|M)} \tag{3}$$

When it comes to the risk modeling of IPS2, the data set is some sequence observation, $D = \{Y_1, Y_2, ..., Y_T\}$, and we wish to predict the next observation, Y_{T+1}, based on the data and models; then the Bayesian prediction

$$P(Y_{T+1}|D) = \int P(Y_{T+1}|\theta, M, D)P(\theta|M, D)P(M|D)d\theta dM \tag{4}$$

integrates the uncertainty in the model structure and parameters.

In the following research, the method based on DBN for IPS2 risk modeling and analysis will be further developed with auxiliary tools.

Proposed framework for IPS2 risk management

The International Standard Organization (ISO) has provided us with a general framework for risk management applicable for all kinds of areas.[38] The framework only offers a cursory operational outline, while concrete processes, methods, and tools still need to be tailored in accordance with special features of IPS2. As depicted in Figure 1, a new framework for IPS2 risk management is proposed in this work. The whole process is divided into two stages, IPS2 modeling and risk management processes. Specific methods and tools developed for each step are also marked in the flow chart.

This new framework for IPS2 risk management is developed by integrating theories of value engineering, system analysis and mathematical modeling. The incorporation of different methods and elements in the framework is organized as follows:

1. Value engineering is applied to analysis value creation process in three dimensions, which includes value recognition, value proposition and value delivery.
2. System analysis is used to make the hierarchy more clear and accurate in stakeholders and system component analysis, business structure–process depiction and risk recognition.
3. Then, mathematical modeling methods, including DBN and entropy reduction value (ERV), are used for data processing and graphical visualization.

Detailed work is carried out in sections "IPS2 modeling" and "IPS2 risks modeling and analysis." And before that, the novelty and new features of the framework are analyzed. Four characters make it a new framework and different from others, which are as follows:

1. Although it is built based on ISO standard,[38] details of every step are further developed to adapt to IPS2 risk analysis specifically, for example, the IPS2 modeling process.
2. Every risk management framework is applicable to particular domain, and in the area of IPS2 risk management, no systematic research has been conducted before this work.

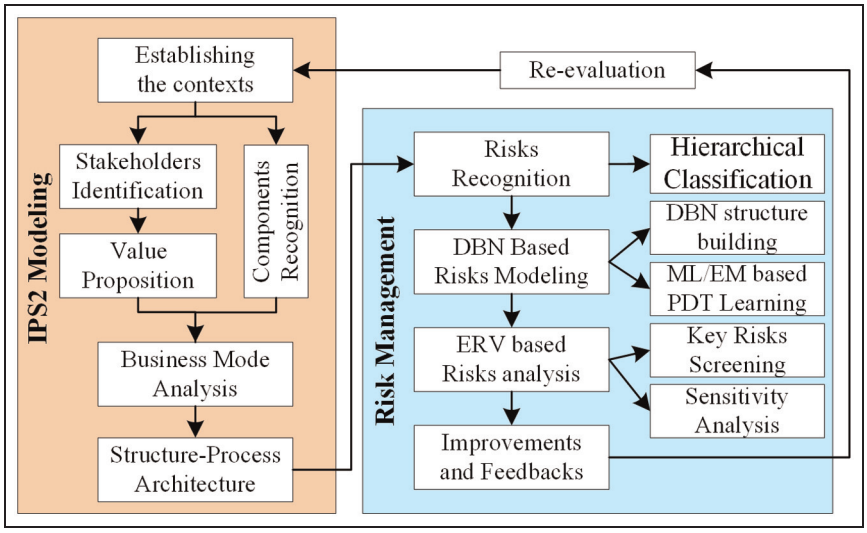

Figure 1. Proposed framework for IPS2 risk management.

3. The integrating theory of value engineering, system analysis and mathematical modeling of DBN and ERV is also very rare in the existing work.
4. The methods of Structure–Process Architecture and merging operation of graphic risk units are all first proposed in this work.

IPS2 modeling

Establishing the external and internal contexts

As IPS2 is such a system that relies more on stable cooperation relationships and contract credits, it is more sensitive to the change in external and internal conditions and boundary constraints. Under different backgrounds and circumstances, risk factors, effect chains, corresponding analytical methods and results can vary widely.

Similar to the risk analysis of mechanical systems, ecosystems or investment portfolios, while considering its specific characters, the external and internal contexts of an IPS2 can be sorted as follows:

External contexts may include, but is not limited to, the following:

1. The social and cultural, political, legal, regulatory, financial, technological, economic, natural and competitive environment, whether international, national, regional or local.
2. Key drivers and trends having impact on the objectives of the organization.
3. Relationships with, and perceptions and values of, external stakeholders.

Correspondingly, internal contexts may include, but is not limited to, the following:

1. Governance, organizational structure, roles and accountabilities.
2. Policies, objectives and the strategies that are in place to achieve them.
3. Capabilities, understood in terms of resources and knowledge (e.g. capital, time, people, processes, systems and technologies).
4. Information systems, information flows and decision-making processes (both formal and informal).
5. Relationships with, and perceptions and values of, internal stakeholders.
6. The organization's culture.
7. Standards, guidelines and models adopted by the organization.
8. The form and extent of contractual relationships.

Stakeholder identification, component recognition and value proposition

Aligned with the goal of value co-creation, all related stakeholders in the IPS2 network should be identified, and their needs and value proposition should be clarified. Based on the business chain analysis of IPS2, stakeholders can be classified into several main categories, including research and development (R&D) institutes, suppliers, manufacturers, retail traders, service providers, customers, governments, environments and so on. Every category, as a sub-system, can be subdivided into more detailed indivisible units. Then, we can get the organization breakdown structure (OBS) of an IPS2.

Value propositions of stakeholders are measured with the arithmetic value of inputs and outputs. A template, taking manufacturers and customers as examples, for value proposition analysis is given as shown in Table 3.

Apart from stakeholders, IPS2 have many other constituent parts, such as products, tools and materials. They are passive inanimate objects in the system. But their state changes are also the main sources or

Table 3. Template for stakeholder identification and value proposition analysis.

No.	Stakeholders	Inputs	Outputs	Value propositions
1	Manufacturers	Human resource, capital, equipment, materials, etc.	Products, market share, wastes, equipment amortization, etc.	Maximum beneficial outputs Higher market share and brand value Minimum investments Less harmful outputs
2	Customers	Money, manual labor, brainwork, etc.	Usage experience, profits, product faults and aging, etc.	Best experience and highest profits Least money and labor costs Low failure and aging rate
…	…	…	…	…

Outputs include both the beneficial and harmful outputs.

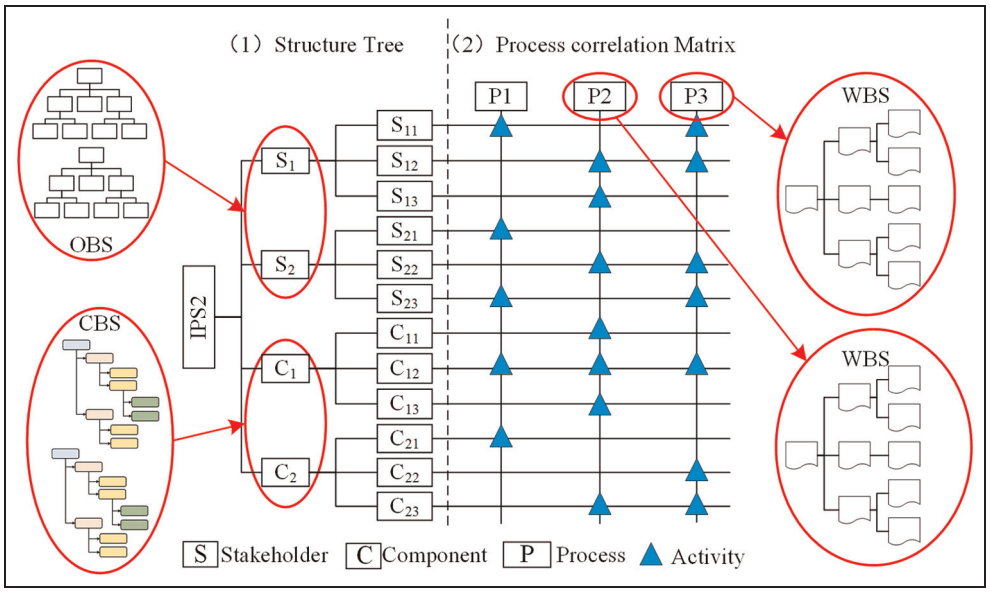

Figure 2. Conceptual IPS2 structure–process correlation model.

representations of risks. These constituent parts, or formally called components, should be recognized and listed in the way of component breakdown structure (CBS). The values of components come from the cognition and perception by stakeholders.

Business and structure modeling of IPS2

Following the last step work of stakeholders and system components identification, linkages and interactions between them, which keep the system running, should be found out. Because of the linkages, IPS2 connects all the discrete individuals and forms a vast and complex relational network. And as a result of interactions, information, materials and capital can flow along linkages and the values are created for all the participating system stakeholders.

The structure–process correlation model is used. The structure tree obtained from the OBS and CBS is applied for system hierarchy analysis. Meanwhile, the process matrix is used for interaction and work breakdown structure (WBS) analysis. Then, a conceptual IPS2 structure–process correlation model is established, as depicted in Figure 2, in which both linkages and interactions in an IPS2 are very convenient to be described and coded in the following risk modeling and analysis processes.

IPS2 risk modeling and analysis

Risk recognition

Risk recognition is defined as the process of determining risks that could potentially prevent the program, enterprise or investment from achieving its objectives.[38] The process involves the recognition of risk sources, hazard factors, peril events and their potential consequences. Basically, a risk can be represented by an attribute set and a correlation set. The attribute set is used for risk classification and character description, while the correlation set is used for the building of basic risk units.

Attribute set is represented as {*source*, *risk objects*, *natures*, *influence sphere*, *variability* and *controllability*}, which is actually a multi-dimension classification method for risks, as shown in Table 4. With attribute set, we can get a full understanding of risk characters.

Table 4. Dimensions for risk classification.

Dimensions	Detailed attributes			
Sources	Natural	Social	Economic	Political
	Technical	Legal	Organizational	Operational
Risk objects	Property	Personal	Liability	Credit
Nature of risks	Pure	Speculative	Income	
Influence sphere	Fundamental	Specific		
Variability	Dynamic	Static		
Controllability	Controllable	Uncontrollable		

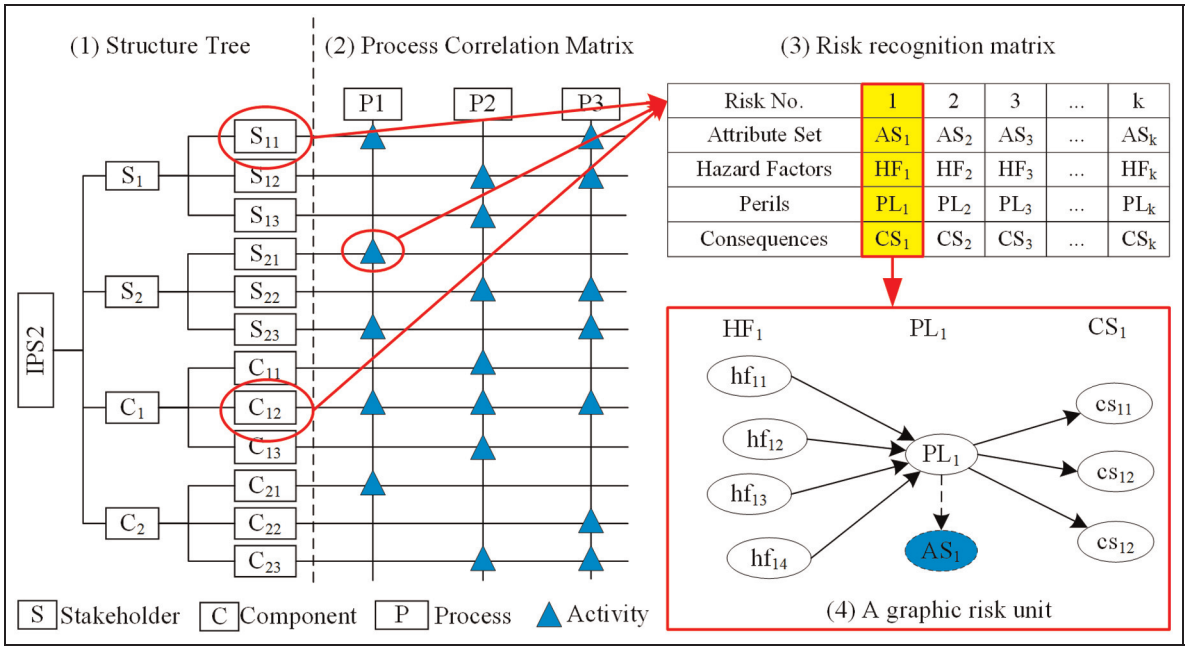

Figure 3. Proposed IPS2 risk recognition process.

The correlation set is described as $\{HF, PL, CS\} = \{\{hf_1, hf_2, \ldots, hf_n\}, PL, \{cs_1, cs_2, \ldots, cs_n\}, AS\}$, in which HF is the set of hazard factors, PL is the peril event, CS is the set of consequences of a peril event and AS is the attribute set. For any risk, it may have multiple hazard factors and consequences, but the peril event is its unique identity. Those units without hazard factors are called root causes and units without further related consequences are called ultimate outcomes.

As shown in Figure 3, the proposed risk recognition process is the combination of IPS2 structure–process correlation model, attribute set and correlation set. The goal is to establish a systematic relationship and structure mapping and then get all the possible graphic risk units.

While IPS2 structure–process correlation model presents all the possible analysis units, attribute set provides a multi-dimension guideline for sorting out all the possible risks. Constituent elements can be recognized using the correlation set and decomposed them into detailed hazard factors, peril events and consequences. Then a risk recognition matrix is obtained as shown in the top right corner of Figure 3. Then, we can transform every column of the risk recognition matrix into independent graphic risk units shown in the bottom right corner of Figure 3.

Risk modeling with DBN

Preliminary structure building of risk DBN model. As a result of the last step, the risk recognition matrix and graphic risk units are obtained. Risk items should not be considered in isolation and statically. Moreover, IPS2 risks should be modeled and analyzed at the system level.

Based on that consideration, the authors tried hard to find out the correlations between different risk items. Although peril events are the unique identity of risks, different risks share similar hazard factors or lead to the same consequences. Meanwhile, the consequences of a risk may be the hazard factors of another risk. By merging the same nodes of different graphic risk units and connecting risks with causality relationships, a risk correlation network can be established; an example is given in Figure 4. The graph we get in Figure 4(b) is just a perfect prototype of BN.

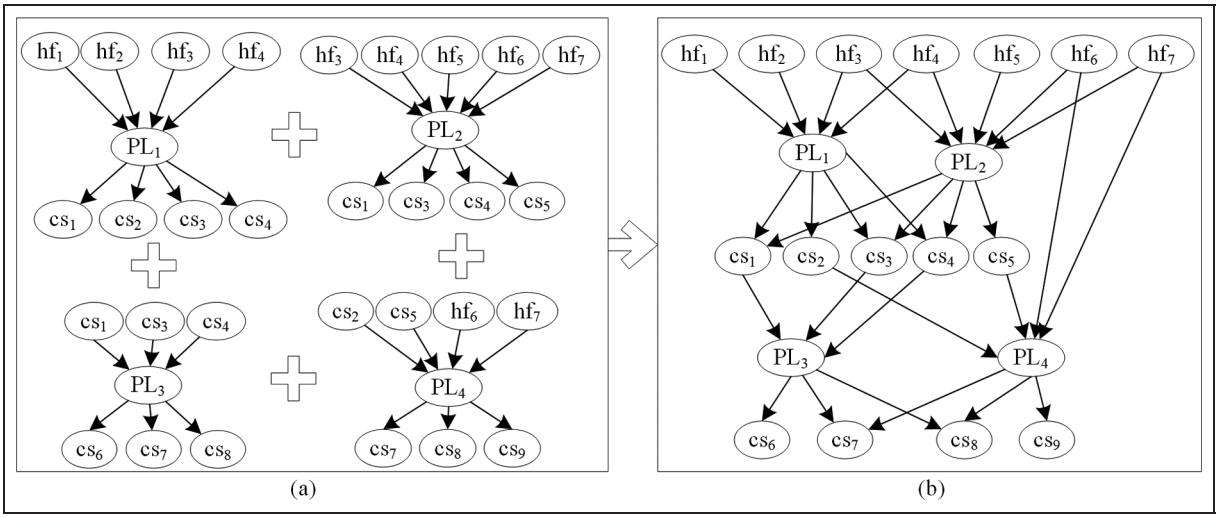

Figure 4. An example of merging operation of graphic risk units: (a) independent risk units and (b) merged risk correlation network.

Through the merging operation of graphical units, we can get a static and fixed structure BN. As we all know, the contexts, stakeholders, system components and activities of an IPS2 may change over time. Time axis should be considered as an important dimension for risk analysis. To solve the problem, the DBN-based risk modeling method is introduced.

As shown in Figure 5, with a time shift of Δt from t_1 to t_2, risk items may have transformation rates. Through the merging operation to graphic risk units at t_2, we can get a totally new IPS2 risk BN. With explicit transformation rules, future risk BN structure and parameters can be inferred from the current and historical conditions.

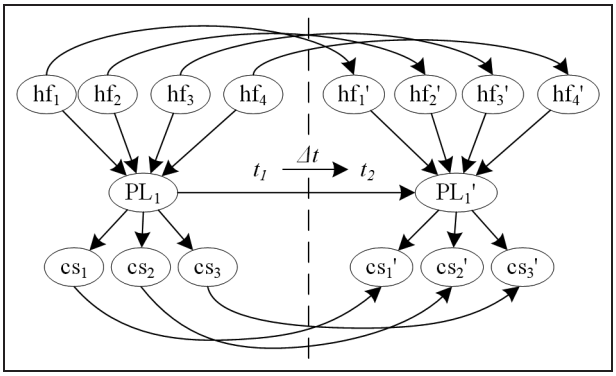

Figure 5. Proposed DBN model for IPS2 risk unit modeling.

Probability distribute learning and structure modifying. The preliminary established DBN graphical structure is not more than an inaccurate draft or skeleton. Only with necessary accurate data supporting, it can become meaningful. Apart from the nodes and the set of directed arcs, the conditional probability table (CPT) is another important element to describe the possible states of different nodes and their mutual interactions. Generally, the probability distribution can be obtained from expertise experiences or massive historical data, or the combination of both. Data obtained from expertise experience usually have strong subjectivity. In the meantime, when it comes to complex IPS2, the efficiency, accuracy and reliability of experts' manual and brain working are doubtful. A more reliable and efficient CPT learning method is needed.

For those traditional and mature industries transforming to IPS2 business mode, they have years or even decades of business data accumulation. With the maximum likelihood (ML) estimation model and expectation model (EM) estimation model, which Ghahramani[36] developed for DBN learning, we are able to construct the CPTs from massive data. ML solves those problems with complete data, while EM can solve DBN models with hidden variables.

At the end of the calculation process, the whole network is able to be driven by arc connections and CPT data. In particular, the IPS2 risk model can be used in two ways. First, at a fixed time point, with given internal and external conditions, states and CPTs of nodes in consequence layer can be calculated. Second, with historical and newly acquired data, the current model can be modified. In addition, the model structure and the corresponding CPTs of the next moment can be inferred.

ERV-based risk grading and analysis

Usually, ultimate outcomes get more concerns, which are represented by the terminal nodes of the DBN model. As resources and energy are limited, risks should have the order of priority to deal with. The occurrence probability and loss degree can both be graded into five levels, from low to high. Using these

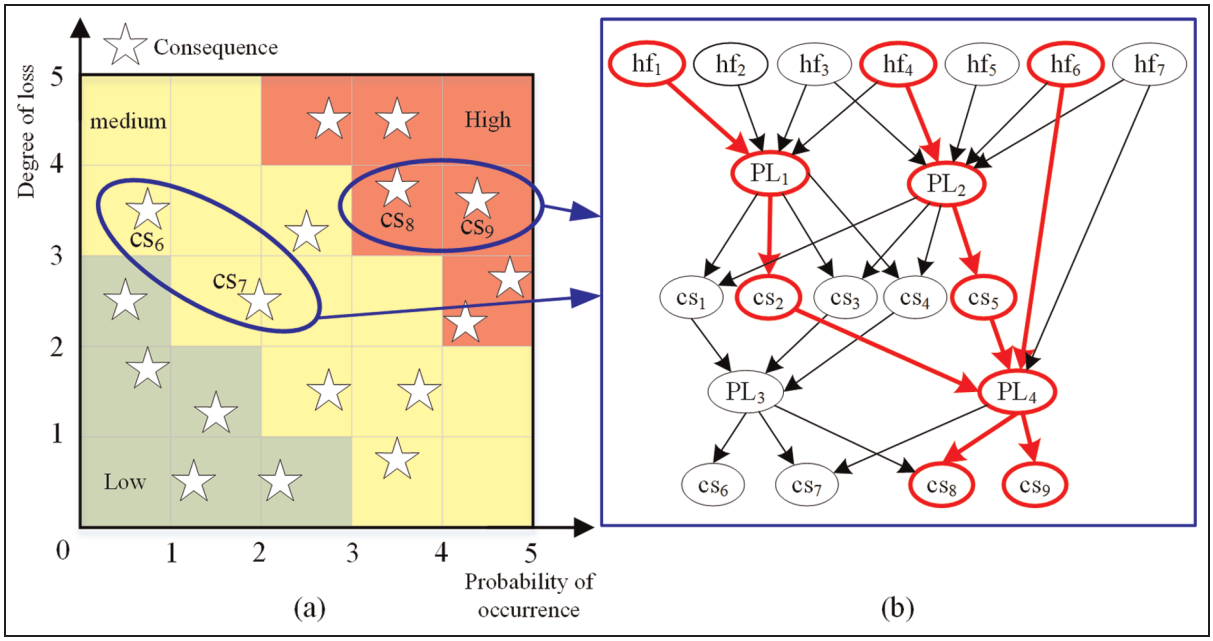

Figure 6. (a) Risk grading matrix and (b) sensitivity analysis for key hazard factors and reaction chain recognition.

two variables as two axes, we can draw a risk grading matrix as shown in Figure 6(a). Then, the terminal nodes can be mapped into the risk grading matrix according to the detailed variable pair values. The matrix is divided into three areas, including low-, medium- and high-risk level areas. Those nodes distributed in the top right corners are obviously the critical risks which may cause great loss to IPS2 and should get enough attentions.

But as we all know, the terminal nodes are just the final outcome and manifestation of risk reaction chains. We can easily find out the last hazard factors that lead to the terminal consequences and try to get rid of their impacts, but that may just be a stopgap which would cost a lot and leave hidden recurrence dangers. In order to find out those key root causes and reaction chains, a method of ERV-based sensitivity analysis is applied. ERV provides a means of evaluating the sensitivity of each node to the terminal nodes.[30] Detailed calculation process is given below.

Suppose X and Y are the two random variables, and x and y are their given values. Then the mutual information ERV of X and Y can be defined as

$$I(X|Y) = H(X) - H(X|Y) \tag{5}$$

in which

$$H(X) = -\sum_{x\in X} p(x)\log p(x) \tag{6}$$

and

$$H(X|Y) = -\sum_{y\in Y}\sum_{x\in X} p(y)p(x|y)\log p(x|y) \tag{7}$$

Detailed proof and derivation procedures can be found in the work of Li and Wang.[39] The measure in formula (5) represents the difference of the a priori and a posteriori entropies of X, that is, the reduction in uncertainty about X by knowing Y. It is noted that $I(X|Y)$ is the information in X about Y, and a high degree of dissimilarity indicates more information X carries about Y.

ERVs of hazard factors are sequenced in descending order. The top ranked nodes are those that influence the final consequences most. An example is given in Figure 4(b), in which the sensitivity of each node is shown by the width of the line. It is obvious that hf_1, hf_4 and hf_6 are the three key hazard factors, while $hf_1 \rightarrow PL_1 \rightarrow cs_2 \rightarrow PL_4 \rightarrow cs_8 \& cs_9$, $hf_4 \rightarrow PL_2 \rightarrow cs_5 \rightarrow PL_4 \rightarrow cs_8 \& cs_9$ and $hf_6 \rightarrow PL_4 \rightarrow cs_8 \& cs_9$ are the three key risk effect chains.

A case study in construction machinery industry

External and internal contexts

The fast development of economy in China extremely improved the volumes of engineering construction business. Sales' quantity of CMs has obtained a tremendous growth in the past several years. As construction machinery market gets saturated gradually, the growth rate of machine sales will slow down in the coming years. Under this circumstance, how to keep the profit growth becomes a huge challenge for all the CM manufacturers.

Because of the huge ownership quantity of CMs in China, aftersales and extended value adding services are turning to be a broad market. So transforming

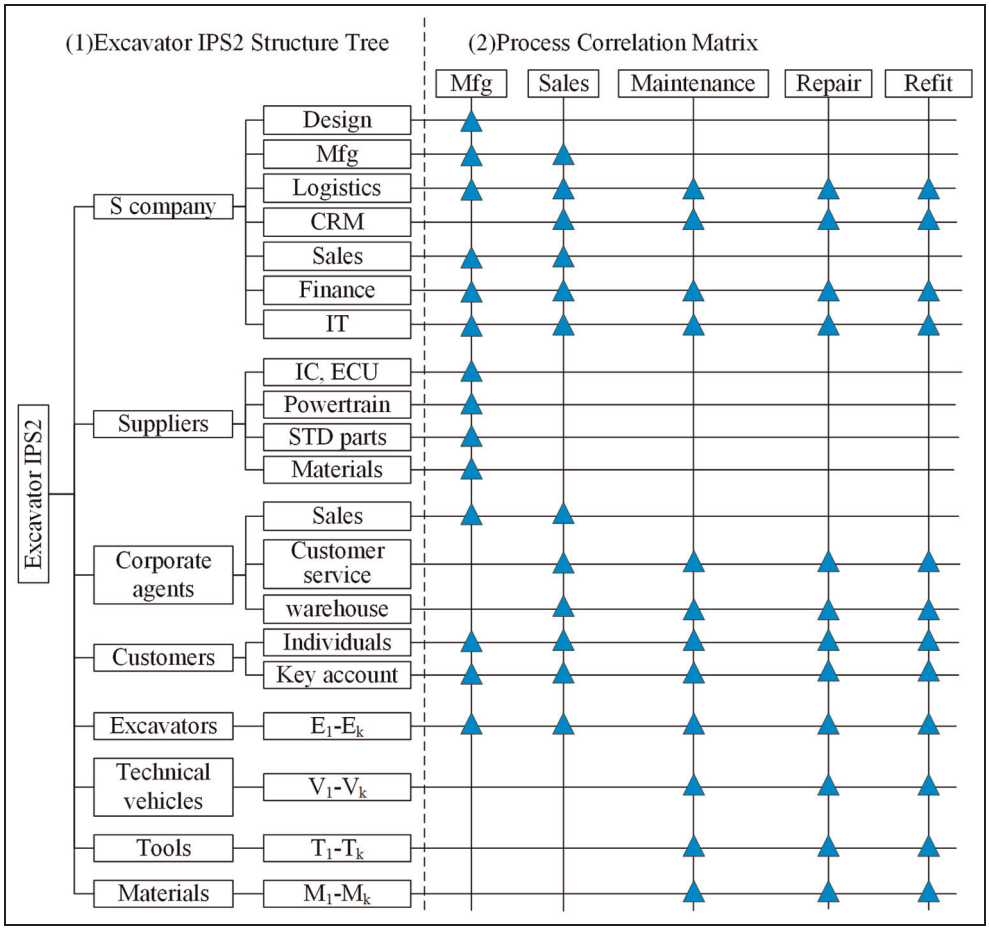

Figure 7. Conceptual excavator IPS2 structure–process correlation matrix.

from manufacturing toward service providing and grabbing service market share is proved to be an effective solution.

S company is a specialized excavator manufacturer and service provider in eastern China. The company's main business includes designing, manufacturing and selling different types of excavators in China. To expand its service business, based on its traditional supplying and sales network, S company has established a systematical service network covering most parts of the country. The service system contains 37 corporate agents, 611 service branches, 1299 technical vehicles and 2448 service engineers all over the country by June 2014. Their slogan is that where there are their excavators, there are their services. The company promises to response in 15 min, arrive in 2 h and remove faults in 24 h. At the same time, business and information systems have been established to support its business transformation. The normal and stable operation of the whole PSS will be key to market and user confident for the company and related to its future profitability.

As the company's service business areas and coverage expand rapidly, handling such a complex and huge system while avoiding loss from risks and uncertainties becomes such a challenging task. With methods developed in this article, we are trying to get this problem solved.

Business model analysis of excavator IPS2

Services for excavators are standardized into three categories, including foundation services, expanded services and value adding services. Foundation services are those must providing basic service items to ensure the availability and normal operation of equipment by at least meeting the minimum standards of the industry. Extended services are those service items derived from customer needs to improve the utility and economic efficiency of the equipment. Value adding services are innovative or highly customized service solutions, which are high-yield characteristic services and are difficult for competitors to imitate in short term.

S company emphasizes the process of value co-creation collaborated with excavator users. Business modes of S company are mainly based on product-oriented IPS2 and use-oriented IPS2. Users now have several choices to obtain an excavator and start their own business. They can just buy an excavator with full payment or installment payment service offered by S company. In another way, they even do not need to own an excavator, they can lease the machine to make money and pay the rents according to usage frequency and duration based on contracts. In this way, S company can achieve sustained gains without continuous producing massive excavators.

Anyhow, no matter whom the machine belongs to, all supporting services can be offered by core S company and its cooperation network. So what users only need is to focus on how to expand their business and gain more chance to improve the utilization and yield rate. As users' revenue and excavators' usability relate to the company's profits, S company and the cooperation network are driven to offer efficient and high-quality services to improve the satisfaction of customers and maintain the performance of the machines.

Based on conceptual IPS2 structure–process correlation matrix, we are easily able to configure out all the related stakeholders in excavator IPS2, including S company, suppliers, corporate agents and customers, as shown in Figure 7. Besides, components of the system include excavators, technical vehicles, tools, materials and so on. Moreover, a list of routine excavator service processes is presented in the right area of Figure 7. All involved roles and possible activities in each process are marked by blue colored triangles in the correlation matrix.

Excavator IPS2 risk modeling

Through face-to-face interviews with chief managers of main departments in S company, including R&D, manufacturing, logistics, sales, Customer Relationship Management (CRM), financial as well as its corporate agents and service centers, we collected their concerns and opinions about risk management in excavator IPS2. Meanwhile, a questionnaire survey was carried out facing frontline staff and users inside and outside S company. A collected list of risk units is obtained using the templates proposed in Table 4 and Figure 2.

Fortunately, the past 10 years' service records of S Company are available. The records contain service requests from users, service responses of S company and its cooperators, problem-solving results, feedbacks from customers and so on. The records have variable data types, including structured, semi-structured and unstructured data. In order that the computer program can read the data and reduce the computational complexity, some pretreatments including irrelevant data cleaning, missing data supplementation, fuzzy data quantification and continuous data discretization are carried out. Excavator IPS2 is a rather complex system, which includes lots of business modules, such as technical support, financial services and maintenance. Excavator maintenance is one important part of the whole IPS2. Limited by our computing ability, in the risk modeling and analysis process, we just take the risk analysis of hydraulic system maintenance failure as an example to demonstrate the validity of the framework and detailed methods.

Hydraulic system maintenance service is one of the most requested services in excavator product–service tasks. With structure–process correlation matrix shown in Figure 7, hydraulic system maintenance service process can get decomposed. As a part of excavator IPS2, hydraulic system maintenance service involves stakeholders including users, manufacturer, service engineers, oil suppliers and other roles with weak effects. Meanwhile, the machine, hydraulic system and oil are other participants in the system. Hydraulic system maintenance service process is organized by those interactions between system components as shown in Figure 8. Attribute uncertainties of system components and the interactions always exist threatening the normal operation of the PSS, which are identified as risk sources in hydraulic system maintenance service process, marked by red words in light blue circles.

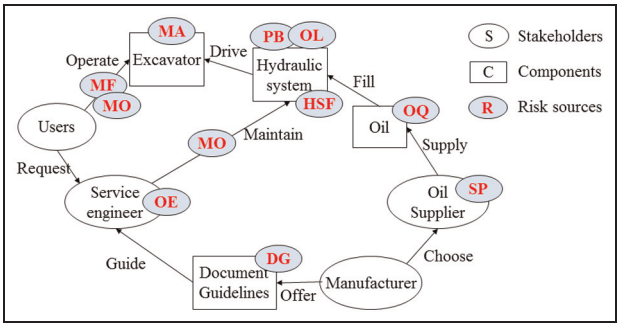

Figure 8. Identification of risks in hydraulic system maintenance service process.
SP: oil suppliers; OE: operator experience; DG: document guidelines; OQ: oil quality; MA: machine age; MO: misoperation; PB: pipeline breaking; OL: oil leak; MF: mechanical failure; HSF: hydraulic system maintenance failure.

Preprocessed data form a large data sheet consisting of lots of data items. Each data item is a complete variables' state record for an entire independent service process. According to the statics for frequency and loss of each risk, they are mapped into the risk grading matrix.

By merging graphic risk units related to hydraulic system maintenance failure, a preliminary structure of the DBN network is established. For further CPT learning, the GeNIe modeling environment is applied, which was developed by the Decision Systems Laboratory of the University of Pittsburgh (http://dsl.sis.pitt.edu). The software is a type of BN and decision support software integrating ML and EM learning algorithm. With the 1000 historical data items offered, CPT of the BN model was constructed through machine learning. The risk modeling result is shown in Figure 9.

Risk analysis based on ERV sequencing

The key hazard factors are identified through sensitivity analysis for all the related nodes. Hazard factors are sequenced according to ERVs in descending order in Table 5. The top three most crucial factors are MF, oil

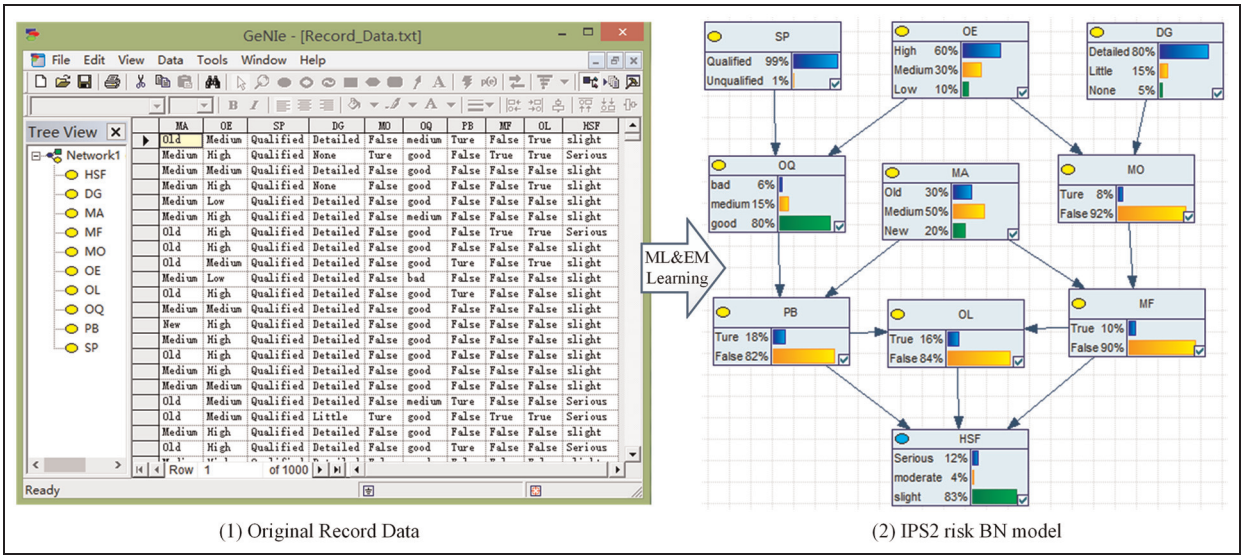

Figure 9. IPS2 risk BN model learning from historical record data.

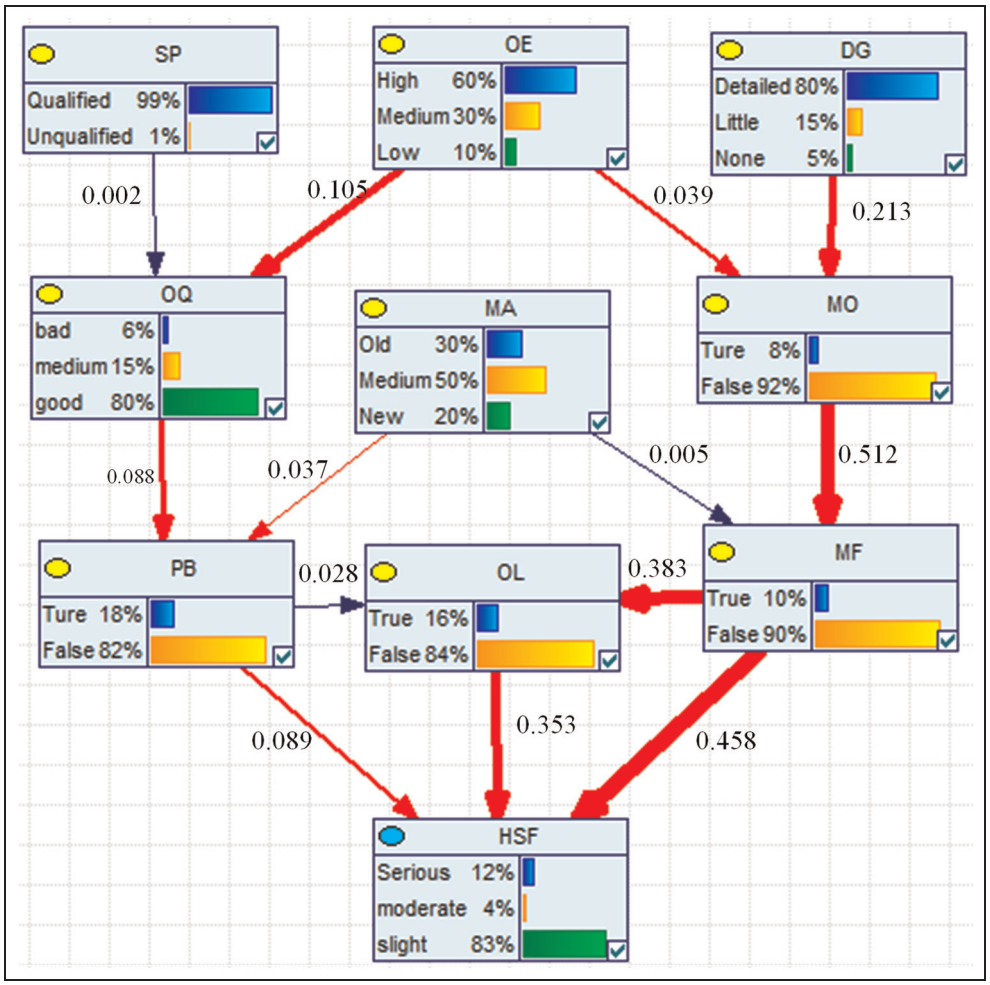

Figure 10. Key risk effect chain recognition of hydraulic system maintenance at time T_1.

leak (OL) and MO. But we find that most of the picked hazard factors are mainly the direct causes. In order to figure out indirect causes in upper reaches, ERVs of every directly related node pair are calculated as shown in Figure 10 at time T_1. According to the results, key effect chains can be mapped along the maximum ERVs

Table 5. Sequenced hazard factors according to ERVs to the result (from T_1 to T_2).

No.	T_1		T_2	
	Node	ERV	Node	ERV
1	MF	0.458	MF	0.380
2	OL	0.353	OL	0.296
3	MO	0.254	MO	0.202
4	PB	0.089	PB	0.101
5	DG	0.048	OQ	0.023
6	OE	0.015	DE	0.015
7	OQ	0.015	DG	0.010
8	MA	0.010	MA	0.009
9	SP	< 0.001	SP	< 0.001

ERV: entropy reduction value; MF: mechanical failure; OL: oil leak; MO: misoperation; PB: pipeline breaking; DG: document guidelines; OE: operator experience; OQ: oil quality; MA: machine age; SP: oil suppliers.

and visualized with red colored lines, the width of which represents the strength of correlations.

By combing the results in Table 3 and Figure 9, at time T_1, three key effects chains can be obviously recognized, including OE → OQ → PB → HSF, OE&DG → MO → MF → OL → HSF and OE&DG → MO → MF → HSF. Meanwhile, the degradation operator experience (OE) and document guidelines (DG) are the root hazard factors for hydraulic system maintenance failure (HSF). The analysis process for time T_2 is the same.

For other top ranked risks recognized in the excavator IPS2, same method and tools can be applied to their analysis processes. Till now, priority is also given for the arrangement of hazard factor control. Targeted work is ready to be carried out for excavator IPS2 risk aversion. Over time, external and internal contexts may get changed. Once the parameters of the chosen hazard factors are under control within a target interval and tending stable, a new loop of risk identification, modeling, analysis and control process begins. By considering the self-change probability of the risk model nodes, DBN-based risk management offers a closed-loop and spiral-type risk management process. An example analysis considering the time factor is given as shown in Figure 11. The interactive relationships do get changed with different initial conditions.

Discussion and conclusion

Transformation to service economy is an irreversible trend and IPS2 is supposed to be the future business mode solution. New interactive relationships lead to the phenomenon of risk transfer and calls for new methods and tools for IPS2 risks management. Based on previous research work of IPS2 modeling methods and general risk management frameworks, they are further developed in this work. Main innovative contributions of this work include the following:

- Developing the template for stakeholder identification and value proposition analysis, as well as the conceptual structure–process correlation matrix for IPS2 modeling.
- Proposing multi-dimensional IPS2 risk classification method, graphic risk unit–based risk recognition and risk DBN structure modeling with merging operation approach, and moreover DBN CPT learning based on ML and EM algorithm.
- Putting forward risk grading matrix and ERV sensitivity analysis based on key hazard factor recognition and visualized graphical key effect chain identification.

The verification results gained from the case study of excavator IPS2 risk management show that the steps of the proposed process are closely related. The IPS2 modeling method is more practical than the traditional scene graphs and more suitable for further risk recognition and modeling. The graphic risk unit–based risk modeling is more operable and straightaway both for manual and computer processing. Risk reasoning of DBN can be obtained from ML and EM learning, which is proved to be with high efficiency and accuracy. Meanwhile, the presentation of visualized risk effect chains is very intuitive.

However, there is still scope for detailed process optimization. Meanwhile, a specialized IPS2 risk management supporting software, which could be integrated into enterprise information decision systems and have computing abilities for large-scale data, is needed. Apart from that, future contributions will mainly focus on risk control process based on IPS2 scheme design and business process reconfiguration, which will benefit firms in more aspects and greater depth. So, this work

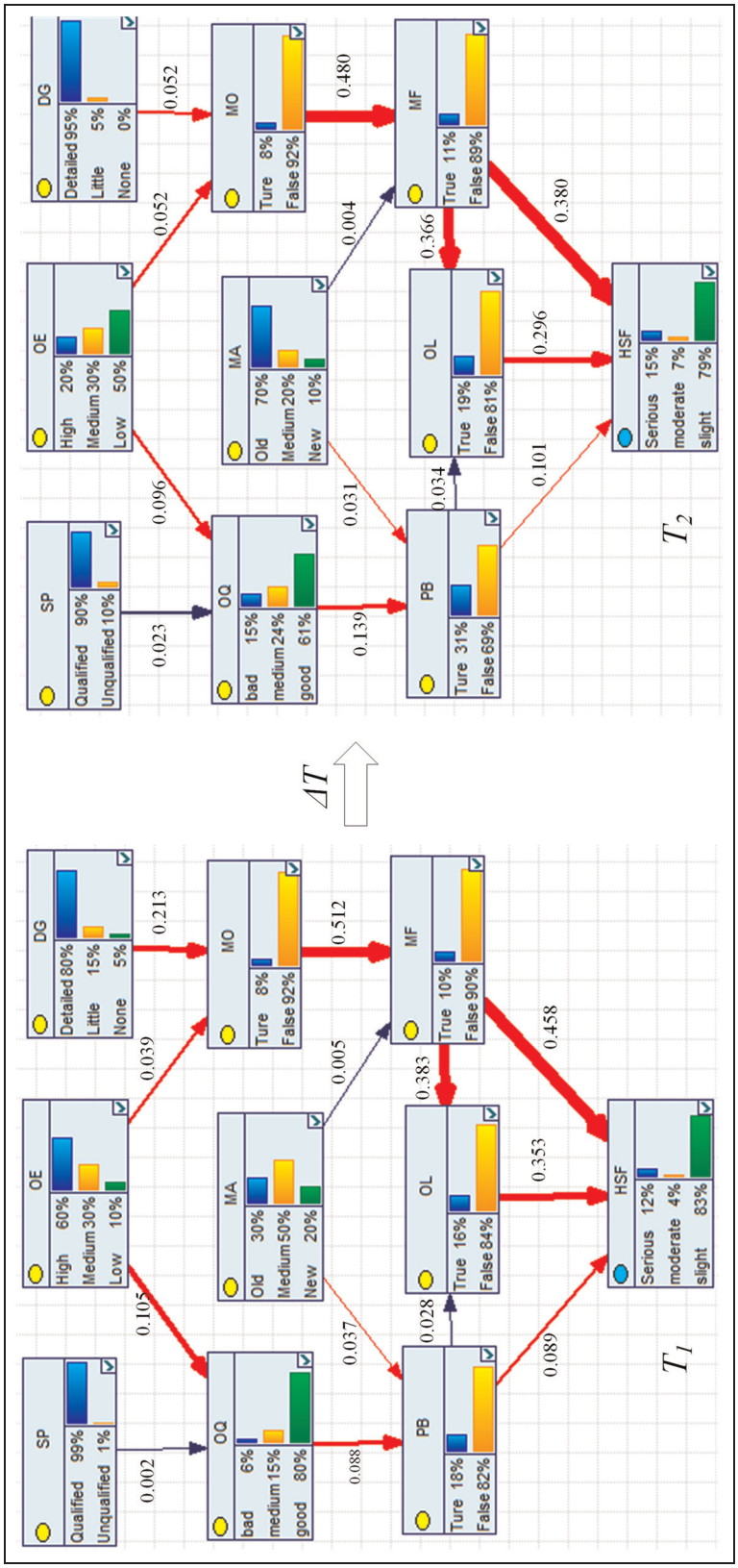

Figure 11. Results considering the time factor from T_1 to T_2.

is just a beginning of the exploration in the area of IPS2 risk management.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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