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MODELING THE KNOWLEDGE FLOW NETWORK FOR COLLABORATIVE DESIGN PROCESS

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ABSTRACT
The design and development of a complex product involves various designers with multidisciplinary knowledge. Knowledge flows between individual designers or teams play a crucial role in determining how well a design task can be performed, and hence the cost and quality of the designed product. Therefore, this paper is devoted to developing a dynamic planning approach for the modeling of a knowledge flow network. Based on the process analysis techniques from Petri Nets, it first defines the concept of a knowledge flow network. The graph based approach is then adopted to represent a knowledge flow network. A dynamic multi-matrix construction method is then developed for the analysis of the knowledge flow network. The approach is especially suitable for describing large-scale design processes involving numerous tasks, designers (or automated computer agents), resources and identifying potential knowledge flow bottlenecks.

Keywords: knowledge flow, design activity, collaborative design, petri nets

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1 INTRODUCTION

The development of complex products within modern organizations has changed dramatically over the past few decades (McMahon et al. 2004). As products becoming increasingly complex, no single individual, team or organization has all the knowledge to treat all the tasks in their design process on its own (Haddad, 2008). In fact, the development of such products requires involving widespread knowledge interactions among numerous designers (Chen et al. 2011). The interactions between any two designers construct a knowledge flow network whether designers are aware of them or not. Knowledge flows are central to all organizational endeavors. Therefore, designing an effective knowledge flow network plays a pivotal role in determining how well a task can be performed. Unfortunately, a variety of social, cognitive and technological barriers often have a negative influence on constructing a functioning knowledge flow network (Zhang et al. 2013). Therefore, it takes effort to develop approaches for the modeling of knowledge flow networks that will be vital to avoiding the unexpected barriers in the design process.

Design research has developed various available methods and tools for design process modeling and analysis. This research can be mainly classified into three groups. The first group focuses on developing a systematic design methodology. For example, the systematic engineering design methodology (Pahl et al. 2007) and the Axiomatic Design model (Suh, 2001). These design methodologies provide designers with a systematic view on engineering design. The second group view design process as a workflow with task dependencies and information exchange (Eppinger et al. 1997; Unger and Eppinger, 2011). Based on this view, the efficient planning of the design process plays a critical role in meeting design constraints. The development of process planning tools has been very active in design society. A set of tools such as Design Structure Matrices (DSM), Signal Flow Graph (Eppinger et al. 1997), Process Evaluation and Review Technique (PERT) and Signposting (Clarkson and Hamilton, 2000) have been developed. Besides the two above groups, some cognitive models, such as the Function-Behavior-Structure (FBS) model (Gero, 1990), the Function-Action-Behavior model (Chen et al. 2011), the Structure-Behavior-Function(Geol et al. 1996), and the Purpose-Function-WorkingSpace-Solution-Behavior (PFWSB) model (Zhang et al. 2012), have been developed for cognitive understanding design and design knowledge. However, today's engineering design has become a knowledge intensive and collaborative process (Zha and Du, 2006), requiring multidisciplinary design knowledge. The modeling of knowledge flow is of critical importance in determining a successful design alternative, which provides valuable insights into design problems for designers. Knowledge flow research is an emerging topic in the knowledge management field (e.g., Nissen, 2002; Zhuge, 2006; Zhang et al. 2012). To the best of our knowledge, few studies have been carried out on knowledge flow in engineering design, and mechanical design in particular, though many design studies have been done related to design knowledge.

This study aims at developing a dynamic planning approach for the designing of a knowledge flow network. This paper introduces the concept of a knowledge flow network and modifies Petri Nets model to define and represent this knowledge flow network. The graph based flexible modeling approach is then adopted to represent this knowledge flow network. A set of mathematical rules is then built for the analysis of knowledge flow network performance. The remainder of this paper is organized as follows: Section 2 presents definitions of knowledge flow and the knowledge flow network. Section 3 proposes an approach for knowledge flow network representation. This section also provides the techniques for the construction of a multi-matrix for the analysis of the knowledge flow network. Section 4 presents an illustrative case. Limitations are discussed in section 5. Finally, the conclusions are presented in Section 6.

2 DEFINE KNOWLEDGE FLOW NETWORK

According to references (Lu and Cai, 2001; Xu and Jiao, 2009), Petri Nets have the unique advantage of supporting process representation in an explicit graph. Also it provides mathematical tools for quantitatively analyzing the behavior of the design process. However, the knowledge flow process is relatively complex and full of uncertainty compared with workflow process. In this section, the traditional Petri Net is modified to make it more suitable for knowledge flow network modeling.

Definition 1. A knowledge flow in an engineering design process is a passing of design knowledge-need and the right knowledge for the need between knowledge flow nodes. A knowledge flow node a team member or role, or a knowledge portal or process (Zhuge, 2006). A knowledge flow starts and ends at a node. A node's knowledge behavior can be knowledge creation management, knowledge organization management, knowledge transferring management and knowledge application management.

Definition 2. A knowledge flow network in design process (abbreviated as "KFN" later) is a set of items, which we will call knowledge flow nodes (KN), with connections between them, called knowledge flow pathways. KFN represents the designers or automated agent.

A Knowledge Flow Network (KFN) is a nine element $KFN=(P,T,F,I,O,D,S,R,M)$ with a set of labels:

Where

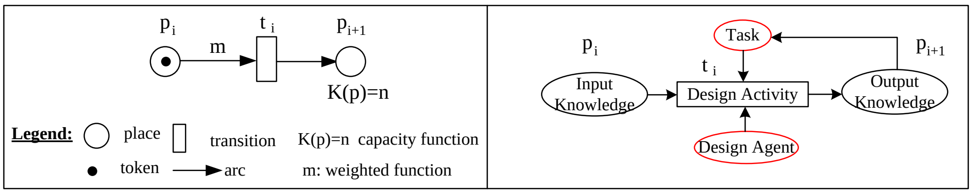
- $P=\forall(PA_i,PG_i)$ is a finite set of places, where $i=1,...,n$, a place refers to a knowledge flow node. Here PA_i is the abstract place that is represented by "◌", it means the knowledge flow node has to fulfill a knowledge acquisition behavior for preparing the token. PG_i is the regular place, the token in this place is represented by "○". For a knowledge flow network, a place designates a design agent, design resource or knowledge need.
- $T=\forall\{t_{Lj},t_{Gj}\}$ is a finite set of transitions, where $j=1,...,m$, a transition refers to the design activities that are executed during the design process. Here t_{Lj} is the abstract transition that is represented by "□". t_{Gj} is the regular transition that is represented by "□". An abstract transition can be expressed by a small scale knowledge flow network.
- $F\subseteq\{(P\times T)\bigcup(T\times P)\}$ is a finite set of directed arcs connecting place and transition, which is the knowledge flow pathways connecting knowledge flow nodes, which are represented by "→".
- $I:(P\times T)\rightarrow N$ is the pathway connecting place to transition, which refers to the input of a knowledge flow node, which is represented as $\cdot t_j\subseteq P$.
- $O:(P\times T)\rightarrow N$ is the pathway connecting transition to place, which refers to the output of the knowledge flow node, which is represented as $t_j\cdot\subseteq P$.
- $D:(T)\rightarrow R^{+}$ is the time constraints for finishing a design task.
- $S=\forall\{S_i\}$ is a finite set of designers, where $i=1,...,k$.
- $R=\forall\{R_i\}$ is a finite set of design resources, where $i=1,...,n$.
- $P\bigcap T=\Phi, P\bigcup T\neq\Phi$ is a finite set of place and transition with no intersection.
- $W:F\rightarrow\{0,1,...\}$ is a weight function, which refers to the number of tokens for firing a transition, i.e., the number of knowledge needs for fulfilling a design activity.
- $K:P\rightarrow\{0,1,...\}$ is a capacity function, which refers to the number of tokens that each place can contain, i.e., the maximum number of design tasks for a node to deal with.
- $M:P\rightarrow\{0,1,...\}$ is the marking of a knowledge flow node, where $\forall p_i\in P:M(p_i)\leq K(p_i)$. Marking is represented by "•". We use "•" to represent trace marking, which means that removing a token from one place will left a trace. Because knowledge is different from a physical artifact, i.e., only a copy of knowledge will be transferred in the knowledge flow process. That is the reason for people to share their knowledge.

3 REPRESENT KNOWLEDGE FLOW NETWORK

3.1 Modeling knowledge flow network

The uncertain nature of design processes makes them difficult to plan （Eckert and Clarkson, 2010）. The knowledge flow network provides a view of the whole design process. Research on design methodologies often provides miracle models for guiding the whole design process; it has the limitations of expressing and evaluating the connections of knowledge flow nodes. An explicit and simple graphical expression of the knowledge flow network is not only convenient for multidisciplinary designers to communicate but also for managers to evaluate the network and find the bottleneck in the network. We use the modified Petri Net method for knowledge flow network modeling.

As shown in Figure 1, a normal Petri Net method uses two types of nodes (i.e. places and transitions) and directed arcs to represent a general process. In a knowledge flow network, places are equal to input and output knowledge of a knowledge flow node, and transitions are equal to design activity, the arcs are equal to the knowledge flow pathway, the weight refers to the types of knowledge needed by the design activity, the tokens are used to represent knowledge sets in the place. As shown in Figure 1(b), each "place-transition-place" represents a knowledge flow meta-node, and all the meta-nodes connected by directed arcs construct a knowledge flow network. It should be note that the flows of knowledge between knowledge flow nodes are driven by the knowledge need, i.e., the places should be with tokens. Design agents and design resources (e.g. software, equipment) are important factors to a successful design; hence the representation of a knowledge flow network should take these factors into account.



(a) Petri Net (b) Knowledge flow meta-node

Figure 1. Schema for Petri Net and knowledge flow node

A simple example of a design knowledge flow network is presented in Figure 2(a), which includes 4 places, 3 transitions and 6 directed arcs. In this knowledge flow network, P2 and P3 are abstract places and T2 is a logic transition. Both the abstract places and the logic transition are small scale knowledge flow networks, which means that these knowledge flow nodes have to plan their knowledge flow networks to finish their design tasks. The planning of a whole knowledge flow network is based on the workflow of design processes, however, each knowledge flow node is able to plan their sub knowledge flow network freely. As shown in Figure 2(b), the abstract place Si represents a functional design of an artifact, and the knowledge flow network for fulfilling this design task includes function decomposition and setting up function structure, etc. Knowledge flow nodes have to acquire and apply design knowledge to finish their tasks and pass knowledge need and knowledge between each other. The logic transition Ti (see Figure 2(c)) represents a design analysis activity, which is further planned to a knowledge flow network. The network includes several knowledge flow nodes, such as design modeling, determining input and output parameters, writing reports, etc. Design Knowledge flows between each nodes while preparing the right knowledge for finishing the task of Ti.

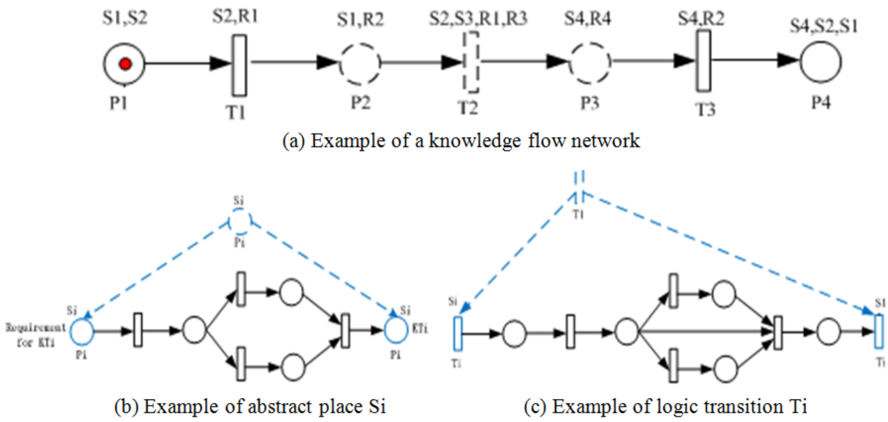


Figure 2. An example of a knowledge flow network in collaborative design process

3.2 Rules for knowledge flow analysis

The Petri Net technology both provides a graph based approach to modeling the design process and a mathematical rule for process analysis. The operational condition of a knowledge flow network and the rule for evaluating the dependency of knowledge needs, design tasks, designers, design resources in a knowledge flow network are proposed as follows. The definition proposed by Cai and Lu (2001) for the representation of a collaborative design process is employed and modified to meet the need for the representation and analysis of the knowledge flow network.

The process of a knowledge flow node in finishing a design task consists of transforming the initial marking into a new marking. Fulfilling a design activity includes two operations, i.e. removing a token from each $p \subseteq \bullet t$ and adding a token to each $p \subseteq t\bullet$. The operational condition of the knowledge flow network can be defined as.

Definition 3. The operational condition of a knowledge flow network is that $\exists \forall p \in \bullet t : M_i(p) > 0$. Fulfilling design activities in a state $M_i(p)$ will lead to the next state $M_{i+1}(p)$, which can be calculated by

$$M_{i+1}(p) = \begin{cases} M_i(p) - 1, p \in \bullet t \\ M_i(p) + 1, p \in t\bullet \\ M_i(p), otherwise \end{cases} \tag{1}$$

Thus, the execution of the knowledge flow process in a knowledge flow network can be represented by a task operation sequence $f=(t_1,t_2,\ldots)$, i.e., a series of knowledge-based design activities (e.g. knowledge integration or knowledge application). The design activities will lead to a series of design knowledge flows, which relates to the transformation of the marking $M_0 \rightarrow M_1 \rightarrow \ldots$

The identification of knowledge flows in a knowledge flow networks node can be evaluated by assessing the state (i.e. active or no-active) of the places. The state transformation of design knowledge can be expressed by

$$M^T = M_0^T + A \cdot N_f^T \tag{2}$$

Where, matrix A (named as P-T matrix) represents the relationship of knowledge need and design tasks; $N_f^T = [n_1, n_2, \ldots]$ is the times of transitions in the operation sequence $f=(t_1,t_2,\ldots)$. For example M=[0,0,0,0,1] represents that the knowledge flow process is finished, while M=[0,0,0,1,0] shows that knowledge flow node 4 is active, which means that the node has knowledge need, and knowledge flow is also active.

The P-T matrix is used to denote the dependency of knowledge need and design task in a knowledge flow network, which can be calculated as follows.

Definition 4. The P-T matrix $A=[a_{i,j}]$is defined over all of the knowledge needs $P=(p_1,p_2,\ldots,p_n)$ and design tasks $T=(t_1,t_2,\ldots,t_m)$, where

$$a_{i,j} = \begin{cases} 1, t_j \in \bullet p_i \\ -1, t_j \in p_i\bullet \\ 0, otherwise \end{cases} \tag{3}$$

In a collaborative design process, the dependency matrix of the design tasks T-T matrix is used to recognize the critical task that relats to other tasks (Lu and Cai, 2001). In a knowledge flow network, using the T-T matrix makes it easy to identify the tasks related bottlenecks to knowledge flow.

Definition 5. A task dependency matrix $B=[b_{i,j}]$, which is defined over all the tasks $T=(t_1,t_2,\ldots,t_m)$, where

$$b_{i,j} = \begin{cases} 1, t_i\bullet \cap \bullet t_j \neq \Phi \\ 1, (\bullet t_i \cap \bullet t_j \neq \Phi) \vee (t_i\bullet \cap t_j\bullet \neq \Phi) \\ 0, otherwise \end{cases} \tag{4}$$

Where, the situation $t_i^{\bullet} \cap {}^{\bullet}t_j \neq \Phi$ refers to the sequential dependency of design tasks, while the situation $\left({}^{\bullet}t_i \cap {}^{\bullet}t_j \neq \Phi\right) \vee \left(t_i^{\bullet} \cap t_j^{\bullet} \neq \Phi\right)$ refers to the concurrent dependency of design tasks. In both situations the dependency factors are set to 1, otherwise the factor is set to 0.

The relationship between designers and design tasks is represented by a task assignment matrix (i.e. the S-T matrix). In a knowledge flow network, the S-T matrix is used to identify designer-task related knowledge flow bottlenecks. It is easy for design managers to coordinate designers with proper design tasks. The matrix is defined as follows.

Definition 6. The S-T matrix $M=[m_{i,j}]$ is defined over the designers set $S=(s_1,s_2,\ldots,s_k)$ and design tasks set $T=(t_1,t_2,\ldots,t_m)$ with the value

$$m_{i,j} = \begin{cases} 1, t_j \in \{t \mid s_i(t)\} \\ 0, otherwise \end{cases} \tag{5}$$

Where $\{t \mid s_i(t)\}$ is a design tasks set assigned to a designer. If a designer is assigned a design task, then the dependency factors is set to 1, otherwise the factor is set to 0.

The dependency of design resource and designer is represented by a R-S matrix. In a knowledge flow network, the R-S matrix is used to identify knowledge flow bottlenecks due to resources required by designers at the same time. It is easy for design managers to coordinate designers with proper resources. The matrix is defined as:

Definition 7. The R-S matrix $D=[d_{i,j}]$ is defined over the designers set $S=(s_1,s_2,\ldots,s_k)$ and the design resources set $R=(r_1,r_2,\ldots,r_q)$ with the value

$$d_{i,j} = \begin{cases} 1, r_j \in \{r \mid s_i(r)\} \\ 0, otherwise \end{cases} \tag{6}$$

Where, $\{r \mid s_i(r)\}$ is the design resource set required by a designer when he/she has to finish a design task. If a specific resource is required by a designer, then the dependency factor is set to 1, otherwise the factor is set to 0.

To represent the dependency between designers, we define a designer relationship matrix (i.e., S-S matrix). In a knowledge flow network, if two designers belong to the same knowledge flow node, knowledge will flow between them. The S-S matrix is used to identify a designers related knowledge flow bottleneck. Design managers can also use this matrix to coordinate designers with proper knowledge flows. The matrix is defined as:

Definition 8. The S-S matrix $N=[n_{i,j}]$ $N=\left[n_{i,j}\right]$ is defined over a designer set $S=(s_1,s_2,\ldots,s_k)$ with the value

$$n_{i,j} = \begin{cases} 1, \left(s_i, s_j\right) \in P_i / T_i \\ 0, otherwise \end{cases} \tag{7}$$

If two designers belong to the same knowledge flow node, then the dependency factor is set to 1, otherwise the factor is set to 0.

3.3 Matrix for identifying knowledge flow bottlenecks

In order to understand the rules of knowledge flow networks, we use a simple case to apply the rules to build a multi-matrix and use that matrix to identify knowledge flow bottlenecks in a knowledge flow network. The knowledge flow network shown in Figure 2 is transformed into five kinds of matrices (see Figure 3) based on the rules.

$$A = \begin{array}{c} \\ \end{array}\begin{bmatrix} -1 & 0 & 0 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{bmatrix}\begin{array}{l} P1 \\ P2 \\ P3 \\ P4 \end{array} \quad (\text{columns: } T1\ T2\ T3)$$

P-T matrix

$$B = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}\begin{array}{l} T1 \\ T2 \\ T3 \end{array} \quad (\text{columns: } T1\ T2\ T3)$$

T-T matrix

$$M = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{array}{l} S1 \\ S2 \\ S3 \\ S4 \end{array} \quad (\text{columns: } T1\ T2\ T3)$$

S-T matrix

$$D = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}\begin{array}{l} S1 \\ S2 \\ S3 \\ S4 \end{array} \quad (\text{columns: } R1\ R2\ R3\ R4)$$

S-R matrix

$$N = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}\begin{array}{l} S1 \\ S2 \\ S3 \\ S4 \end{array} \quad (\text{columns: } S1\ S2\ S3\ S4)$$

S-S matrix

Figure 3. An example of matrix relationship for a knowledge flow network

According to the P-T matrix, we know that P1 should provide input knowledge for T1 to finish its design task, and P2 is the output knowledge and input knowledge of T1 and T2, respectively. The matrix also shows that the knowledge flow network has sequential flows of knowledge between knowledge flow nodes.

The T-T matrix shows that both T1 and T3 have knowledge flow relationship with T2. The quality of the execution of T2 determines the times of design iterations, and thus T2 is a key knowledge flow node in the knowledge flow network. Due to T2 being a potential bottleneck for this knowledge flow network, the planning of this knowledge flow network should pay more attention to T2.

According to the S-T matrix, designer S2 is assigned the design tasks T1 and T2. The following situations may influence the knowledge flow performance in the knowledge flow network. First, it is difficult for S2 to deal with two design tasks at the same time. Second, S2 may be without enough time to respond to other knowledge flow nodes. Another one is, if T2 depends on S2 to make a design decision, S2 may not able to make such a decision on time due to some issues. In this knowledge flow network, S2 is a potential knowledge flow bottleneck, and thus planning of this knowledge flow network should take these factors into account.

As shown in the S-R matrix, designers S1 and S2 both need resources R1 and R3 to deal with their design tasks. Without planning, there may be a potential timely conflict for them to use the resources. The S-R matrix can be used for a design manager to identify such a bottleneck in a knowledge flow network. Furthermore, a well-planned knowledge flow network is able to avoid wasting time for designers waiting to use the same design resources at the same time, and thus to facilitate efficient knowledge flows.

The S-S matrix shows that there only exists knowledge flows between designer S2 and the other three designers. Therefore, designer S2 has an important role in this knowledge flow network, and the planning of this knowledge flow network should consider the characters of design S2 and evaluate his/her capability.

4 CASE STUDY

This section uses the knowledge flow of a research group in a university, to illustrate the application of the knowledge flow network approach to software development. The software is named the Internal Combustion Engine Lifecycle Performance Digital Prototype (Abbreviated as ICLPDP), which is used to predict tribological and dynamic behavior of the piston-connecting rod-crankshaft mechanism in internal combustion engines. The method developed in this study is to model the knowledge flow network of the development of ICLPDP. In this group, the ICLPDP development team requires participants from various disciplines and resources to support the development process. There are 7 stakeholders and 7 kinds of design resources in the development of ICLPDP, detailed information is illustrated in Table 1.

S1 is the engineer from an R&D center in the automobile industry. Requirement analysis identified two kinds of requirements: (1) customer purpose, and (2) functional requirement. A detailed description of the requirements are given in Table 2. The requirement is the basic input for the development of ICLPDP. An ontological model (Zhang et al. 2012) is used to comprehensively represent the knowledge flow network based on the development process.

Taking designers, resources, requirements, time constraints and tasks into consideration, the knowledge flow network is modeled, which is presented in Figure 4. There are 7 places and 6 transitions in the network, including 5 abstract places and logic transitions, respectively. Colored tokens are used to represent different kinds of knowledge need. Detailed information for transitions and places are given by the forms in Figure 4.

Table 1. Stakeholder and resource for ICLPDP software development

Type	Class	Notation	Description
Stakeholder	Customer	S1	Customer
	Professor	S2	Tribologist
	Lecturer	S3	Engine design
	Graduate A	S4	Engineering design
	Graduate B	S5	Computer science
	Graduate C	S6	Numerical computing
	Graduate D	S7	CAD/CAE
Resource	CAD software	R1	e.g. SolidWorks
	CAE software	R2	e.g. ANSYS
	Developing language	R3	e.g. MS. NET, Fortran
	Computers	R4	e.g. Workstation
	Facility	R5	e.g. Office room
	Engine	R6	e.g. Gasoline engine
	Test-bed	R7	e.g. Pin-on-disc testing machine

Table 2. Input/output class for ICLPDP software design

PFWSB element	Class	Notation
Customer purpose	Calculate frictional loss	CN1
	Evaluate the effects of structural parameter on frictional loss	CN2
	Easily to learn and operate	CN3
Functional requirement	To display lubrication behavior	F1
	To show piston dynamic	F2

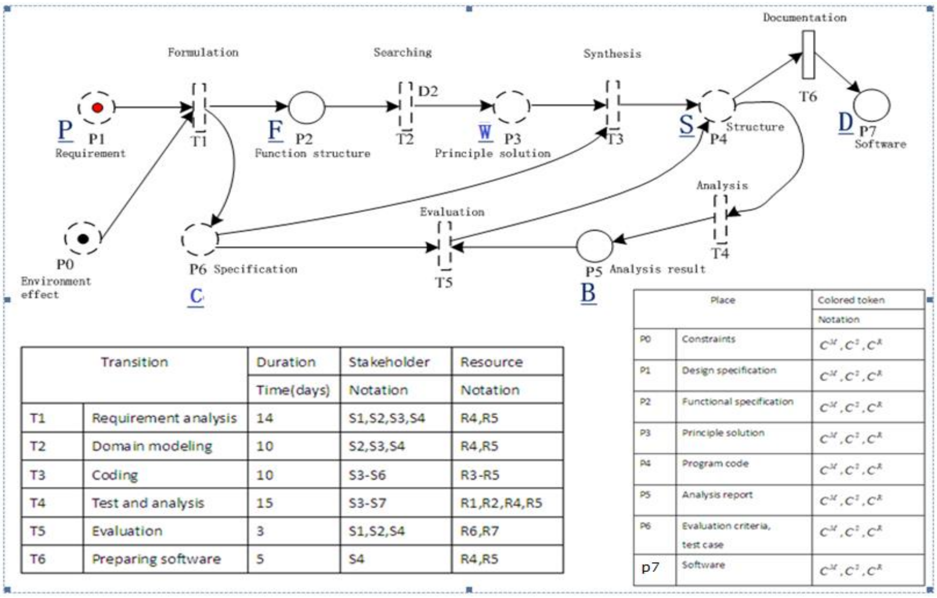


Figure 4. The knowledge flow network of ICLPDP software development

Using the rules, we can transform the graphical knowledge flow network into a multi-matrix (see Figure 5). In all the matrices, the factor 0 or the white blanks represent the independency of two elements and the factors 1 and -1 represent dependency of two elements. The R-S and S-T matrix shows that S4 needs more resources and is assigned too many tasks. It concluded that S4 is a key role in the knowledge flow network and also may be a knowledge flow bottleneck. The S-S matrix shows that there are heavy knowledge flows between designers.

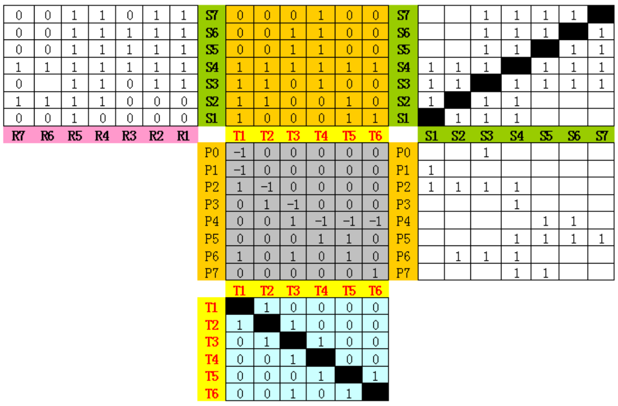


Figure 5. Matrices for knowledge flow analysis

5 DISCUSSION

The flow of knowledge plays a central role in a wide variety of fields, especially in design processes. An efficient planning approach is vital to avoid unexpected bottlenecks and iterations in a knowledge flow network. This study provides managers and designers with a method and tool to clearly view and analyze the whole knowledge flow network. Compare with DSM and other methods，our approach supports the construction of matrices to identify bottlenecks (if any) in knowledge flows.

One limitation of this work is the lack of an industry case to evaluate the approach’s practical benefits. This study constitutes fundamental knowledge flow network research and it focused on the development of theoretical rules and graph based approaches for knowledge flow network modeling and analysis. The multi-matrix based analysis approach could be the core for analyzing potential knowledge flow bottlenecks. In the future, we will select collaborative design cases from companies for the validation and verification of the proposed method.

Another limitation is that this study should provide approaches for the representation of designers and design resources because designers and design resources are key factors in knowledge flow networks. If planning knowledge flow networks with a clear cognition of the characters of these two kinds of elements in knowledge flow networks, it will be valuable to avoiding unexpected bottlenecks that could easily detract from the efficiency of knowledge flow networks. It is another direction for future research.

Furthermore, this study does not build a knowledge flow network planning system. A planning system is able to realize the practical benefits of the the modeling approach and its related analysis method. In our future work, a knowledge flow network planning system will be developed. The functions of a system include (1) supporting a flexible knowledge flow network representation, (2) constructing matrices automatically, (3) providing algorithms for knowledge flow analysis, and (4) managing the information about designers and design resources.

6 CONCLUSIONS

In the knowledge-intensive collaborative design process, design related knowledge is needed to support design performance. However, knowledge is distributed unevenly within the boundary of a collaborative environment. It is therefore a necessary effort to develop methods and tools to facilitate knowledge flow for effective and efficient collaborative design. In recent years, researchers have focused on the development and application of knowledge flow models to industry application and academic research. However, it still lacks methods and tools for planning knowledge flow networks and identifying knowledge flow bottlenecks in an easier manner. Pioneering studies for collaborative design and understanding designers’ knowledge needs formed the basis of understanding the enablers of knowledge flow.

This study develops a Petri Net based approach for knowledge flow network modeling in the collaborative design process. The primary contributions of this study are as follows: (1) The traditional Petri net is extended to serve as a tool for the construction of a design knowledge flow network. In comparison with other knowledge flow models, our approach can provide a graph based flexible modeling approach. (2) Mathematical rules are developed for analyzing knowledge flow networks. Based on the rules, multi-matrices are constructed and used to identify potential knowledge flow bottlenecks. (3) This study takes designers, design resources, design tasks, and knowledge needs as key elements of knowledge flow networks modeling. It also provides tools for evaluating these factors on knowledge flow performance. In summary, this approach can be used to help design managers effectively plan their knowledge flow network in a collaborative engineering design process.

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