Journal of Engg. Research **Vol. 5 No. (4) December 2017 pp.** *155-168*

نظام اكتساب موارد المعرفة لدورة حياة المنتج

بن تشن* و يو باي باي شيه*

* مختبر مفتاح الدولة من النظام الميكانيكي والاهتزاز، جامعة شنغهاي جياو تونغ، شنغهاي، 200240، الصين

الخلاصة

تعتمد القدرة التنافسية الرئيسية للمؤسسة إلى حد كبير على موارد المعرفة. ومع ذلك، لا تزال المؤسسات التقليدية تولي المزيد من الاهتمام للموارد المادية والعمالة. وحتى في بعض المؤسسات الشهيرة الكبيرة، لا تزال موارد المعرفة مجزأة وتوزع في ملفات المشاريع المختلفة. وإذا أمكن تجميع هذه الموارد القيمة للمعرفة وإدارتها على نحو فعال، فإنها ستكون بمثابة الأصول الثابتة للمؤسسات. ولذلك، تم اقتراح نظام اكتساب موارد المعرفة لدورة حياة المنتج في هذه الورقة. ولتوضيح جدوى هذا النظام المقترح، تم تحليل وحدة القدرة الداخلية لمحرك الاحتراق كدراسة حالة.

A knowledge resource acquisition system for the product life cycle

Bin Chen* and, You-bai Xie*

***State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai, 200240, China*

Corresponding Author: chenbinsun@outlook.com(Bin Chen)

ABSTRACT

The key competitiveness of an enterprise largely depends on the knowledge resources. However, traditional enterprises still pay more attention to the material and labor resources. Even in some large famous enterprises, the knowledge resources are still fragmented and distributed in the various project files. If these valuable knowledge resources can be accumulated and managed effectively, they will serve as the fixed assets of the enterprises. Therefore, a knowledge resource acquisition system was proposed for the product life cycle in this paper. To illustrate the feasibility of this proposed system, an internal combustion engine power unit was analyzed as a study case.

Keywords: Acquisition system; enterprise; knowledge resource; product design; product life cycle.

INTRODUCTION

In the old days, the competitiveness of an enterprise mainly depended on the material and labor resources. Nowadays, the situation has changed. The customer demands for the products are becoming increasingly complicated. An enterprise cannot't design and produce competitive products only depending on the rich material or labor resources. Now, the competitive products and designs always involve a large number of knowledge resources in multiple disciplinary domains, such as the creative generation unit for offshore wind power and ocean wave energy (Chen *et al.*, 2016; Chen *et al*, 2016; Chen *et al*, 20162017; Chen *et al*, 2016). The design of this generation unit involves the knowledge resources from mechanism, oceanography, aerodynamics, hydraulics, electrochemistry, etcand so on. On the contrary, a knowledge resource can also be used in many different designs, such as the oriented-explosive phase transition theory (Qiu *et al*, 2015; Qiu *et al.*, 2015; Qiu *et al.*, 2015). This theory can be used in the designs of luminescent displayers, biological labels, vivo CT imagers, etcand so forth.

The knowledge resources play an important role in the enterprises. These knowledge resources are widely used to carry the product life cycle forward. On the contrary, they are also obtained from the product life cycle. These knowledge resources largely support the innovation, competitiveness, and efficiency of the product design and production. If they can become the fixed assets of an enterprises, the competitiveness of this enterprise will be largely promoted and become more stable.

However, traditional enterprises still pay more attention to the material and labor resources. They do notn't realize the importance of the knowledge resources. Even in some big famous enterprises, the knowledge resources are still fragmented and distributed in the project files. When the designers need to reuse the existing knowledge resources, they have to search and extract the knowledge resources from the massive and primitive project files. This process takes a heavy workload, ; thus, the design efficiency will be largely pushed down.

Therefore, a knowledge resource acquisition system was proposed for the product life cycle in this study. The rest of this paper will show the study in five parts, i.e.that is, the knowledge resource flow in the product life cycle, the classification of the new knowledge resources, the standard format of the knowledge resources, the construction of the process of the effective knowledge resource precipitation, and the case study. At the end of this paper, the advantages and disadvantages of this proposed system will be discussed, and the future work will alsobeconclude the paperd.

LITERATURE REVIEW

The knowledge resource acquisition first involves how to represent the knowledge resources. The function-behavior-structure (FBS) model (Gero, 1990; Gero & Kannengiesser, 2004) offers a basic representation for the knowledge resources. In this representation, the knowledge resources are described by three kinds of variables, i.e.that is, functional variables, behavioral variables, and structural variables. However, this representation is still too primitive to describe the knowledge resources effectively. The name method (Chakrabarti, 2004) and the tuple method (Welch & Dixon, 1994) can also be used to represent knowledge resources. However, they are also too simple for the engineering applications. The input-output method (Chen & Xie, 20162017; Chen & Xie, 2017; Chen & Xie, 2017) solves this problem in a new direction. In this method, the knowledge resources are represented by their inputs and outputs based on their function, so that, their details can be described completely. Additionally, the control engineering technologies can be conveniently introduced into this method (Chen & Xie, 20162017), so that, the representation of the knowledge resources can step into the mathematical models.

The above representing methods are helpful to establish the standard format of the knowledge resources. Then, the design and production process in the enterprises should be modeled. The systematic design (Pahl & Beitz, 1996) and the axiomatic design (Suh, 2001; Liu *et al.*, 2016; Chen *et al.*, 2016) are the two mainstreams about of this problem. Based on them, many detailed models were proposed for some specific phases during the product life cycle. (Komoto & Tomiyama, 2012; Camelo & Mulet, 2010; Chen & Xie, 20162017; Schmidt & Chase, 2000; Helms *et al.*, 2009; Kurtoglu *et al.*, 2010). These researches are helpful to in establishing the knowledge resource flow model of the product life cycle and the knowledge resource acquisition mechanism in the administration of the enterprises.

KNOWLEDGE RESOURCE FLOW IN THE PRODUCT LIFE CYCLE

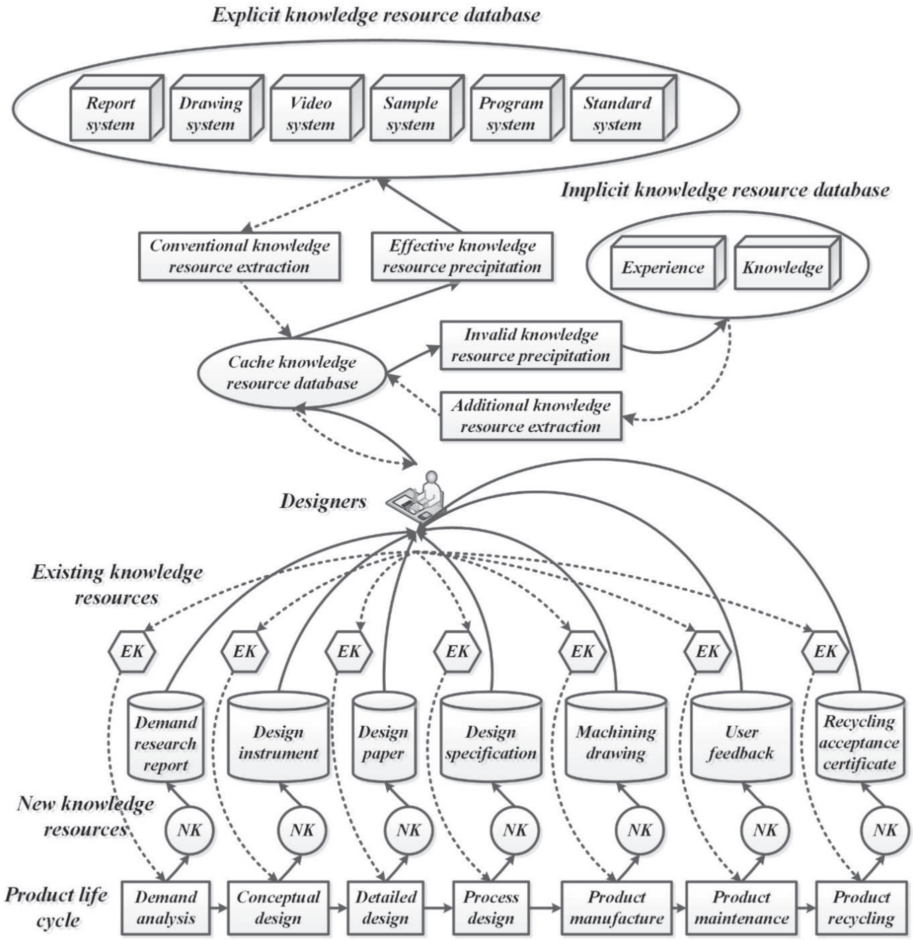

Figure 1. Knowledge resource flow in the product life cycle.

As shown in Figure 1, the product life cycle consists of seven steps, i.e.that is, demand analysis, conceptual design, detailed design, process design, product manufacturing, product maintenance, and product recycling. All these seven steps rely on a large number of existing knowledge resources. The designers need to use these existing knowledge resources to carry take the product life cycle step by step forward. Meanwhile, the designers can also obtain new knowledge resources. These new knowledge resources can be recorded in seven kinds of project files corresponding to the seven steps of the product life cycle, i.e.that is, the demand research report for the demand analysis, the design instrument for the conceptual design, the design paper for the detailed design, the design specification for the process design, the machining drawing for the product manufacturing, the user feedback for the product maintenance, and the recycling acceptance certificate for the product recycling. The new knowledge resources in these files should be standardized, and then, accumulated down as the supplement of the existing knowledge resources. So, the product life cycle is always accompanied by a knowledge resource flow. To manage this flow effectively, some knowledge resource databases should be established for buffering and storage.

As shown in Figure 1, there are three knowledge resource databases involved in the knowledge resource flow, i.e.that is, the cache knowledge resource database, the explicit knowledge resource database, and the implicit knowledge resource database. The cache knowledge resource database is set up temporarily for a specific design project as a buffer. It can be read and written by the designers at any time. Both the required existing knowledge resources and the obtained new knowledge resources are stored in this temporary database. When the design project ends, this database should be closed. Then, most of its knowledge resources should be standardized and accumulated into the explicit knowledge resource database.

The explicit knowledge resource database is a fixed asset of the enterprise, so all the designers in the enterprise can use it effectively and stably no matter which design project they belong to. This database consists of many storage systems, like report system, drawing system, video system, sample system, program system, standard system, etcand so on. During the product life cycle, the designers can extract the required existing knowledge resources from the corresponding storage system into the cache knowledge resource database, and then, these knowledge resources can be visited at any time. This process is called conventional knowledge resource extraction, because it can be completed through the daily administration in the enterprise. On the contrary, the new knowledge resources obtained from the product life cycle should also be inputted into the explicit knowledge resource database from the cache knowledge resource database. This process is called effective knowledge resource precipitation, because once these new knowledge resources are inputted into the explicit knowledge resource database, they actually become the fixed assets of the enterprise.

As for the implicit knowledge resource database, it belongs to the designers. Every designer has his/her own implicit knowledge resource database. This database stores the experience and knowledge this the designer obtained from the former design projects. Actually, these design projects were supported by the enterprise, so the enterprise also made contributions to this database. However, the enterprise does notn't have any effective control on this database. The knowledge resources of this database can be extracted into the cache knowledge resource database only if the designer is willing to share. These knowledge resources can make the extra contributions to the current design project, so, this process is called additional knowledge resource extraction. On the contrary, the designer can obtain new experience and knowledge from the current design project. These new knowledge resources can only deposit into the designer's own implicit knowledge resource database. This process is called invalid knowledge resource precipitation, because the new knowledge resources do notn't become the fixed assets of the enterprise.

CLASSIFICATION OF THE NEW KNOWLEDGE RESOURCES

Based on the knowledge flow model established before, the new knowledge resources obtained from the product life cycle are the important supplement for the explicit knowledge resource database. They can be classified into three kinds according to their contents, i.e.that is, new knowledge resource elements, new knowledge resource combinations, and mixed new knowledge resources. A new knowledge resource element is a brand new knowledge resource. This kind of knowledge resources are is very hard to obtain, so, they are the most precious. A new knowledge resource combination is made up of several existing knowledge resources organized in a new way. This kind of new knowledge resources can help the designers tosolve new design problems with the old knowledge economically. In the product life cycle, most of the new knowledge resources are the new knowledge resource combinations. As for a mixed new knowledge resource, it is the mixture of the first two kinds of new knowledge resources.

STANDARD FORMAT OF THE KNOWLEDGE RESOURCES

The new knowledge resources obtained from the product life cycle are first stored in the cache knowledge resource database temporarily. When the design project ends, they should be sent to the explicit or implicit knowledge resource databases through the effective knowledge resource precipitation or the invalid knowledge resource precipitation, respectively. Among them, only the knowledge resources sent to the explicit knowledge resource database are the sustainable assets of the enterprise. These knowledge resources should be carefully processed and standardized, so that, they can be effectively precipitated into the explicit knowledge resource database. All these knowledge resources have two unique features, ; i.e.that is, they can be structured, and they can be standardized. The first feature means the knowledge resources can be simplified, modularized, and finally represented, so that , the enterprise can effectively reuse the knowledge resources. As for the second feature, it means the knowledge resources can be standardized based on a standard format, so that, they can be effectively circulated among the different departments in the enterprise. With the above two features, the knowledge resources can be smoothly transported and reused in the enterprise.

The knowledge resources with the above two features can be standardized based on the standard format as shown in Table 1. In this case, the knowledge resource has seven basic attributes, i.e.that is, knowledge resource number, creating time, creating unit, creating designer, design project, disciplinary fields, and keywords. Here, knowledge resource number is the identity of this knowledge resource. Based on it, the departments in the enterprise can position and manage this knowledge resource. As for the other six attributes, they are helpful for the designers to search the required knowledge resources in the explicit knowledge resource database. The main content of the knowledge resource consists of six parts, i.e.that is, problem, principle, solution, input information, output information, and additional information.

Table 1. Standard format of the knowledge resources.

Knowledge resource number: 100	**Creating time:** 26/10/2015	**Creating unit:** ICE Analysis and design center	**Creating designer:** Xiao Ming
Design project: Piston-liner design in ICE	**Disciplinary fields:** Solid mechanics	**Keywords:** Piston skirt, stiffness matrix	
Problem: Calculate the stiffness matrix of a piston skirt. **Principle**： If a piston skirt is meshed into enough amount of grids (assume that it is meshed into m rows and n columns.), its stiffness can be represented by its stiffness matrix as follows.			

$$K = \begin{bmatrix} k_{11} & k_{12} & \cdots & k_{1n} \\ k_{21} & k_{22} & \cdots & k_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ k_{m1} & k_{m2} & \cdots & k_{mn} \end{bmatrix} \quad (1)$$

Here, k_{ij} represents the stiffness of the grid node (i, j) , and it can be figured out by the following equation.

$$k_{ij} = \frac{p_{ij}}{\delta_{ij}} \quad (2)$$

So, if the loading and deforming situations of all the grid nodes are known, the stiffness matrix of the piston skirt can be figured out as follows.

$$K = \begin{bmatrix} \frac{p_{11}}{\delta_{11}} & \frac{p_{12}}{\delta_{12}} & \cdots & \frac{p_{1n}}{\delta_{1n}} \\ \frac{p_{21}}{\delta_{21}} & \frac{p_{22}}{\delta_{22}} & \cdots & \frac{p_{2n}}{\delta_{2n}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{p_{m1}}{\delta_{m1}} & \frac{p_{m2}}{\delta_{m2}} & \cdots & \frac{p_{mn}}{\delta_{mn}} \end{bmatrix} \quad (3)$$

Solution：
With the help of CAE tools, the 3D model of the piston skirt can be constructed. Then, mesh the model under the certain regulation as shown in Figure 2. After the loading process is simulated as shown in Figure 3, the deforming situations of all the grid nodes can be outputted as shown in Table 2. Finally, the stiffness matrix can be figured out.

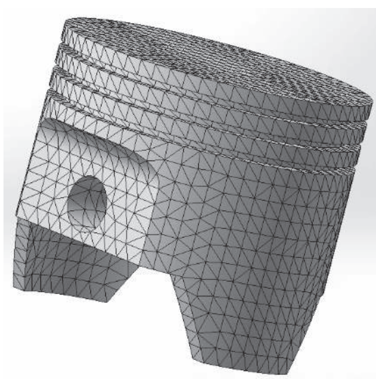

Figure 2. Mesh the 3D model of the piston skirt

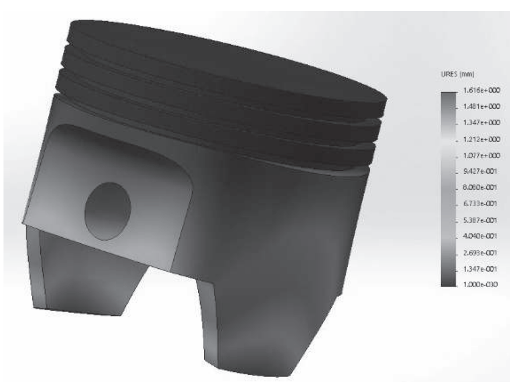

Figure 3. Simulate the loading process

Table 2. Calculate the stiffness matrix

Grid node number	Deformation (m)	Pressure (Pa)	Stiffness (Pa/m)
$(1,1)$	δ_{11}	p_{11}	p_{11}/δ_{11}
$(1,2)$	δ_{12}	p_{12}	p_{12}/δ_{12}
…	…	…	…
$(1,n)$	δ_{1n}	p_{1n}	p_{1n}/δ_{1n}
$(2,1)$	δ_{21}	p_{21}	p_{21}/δ_{21}
$(2,2)$	δ_{22}	p_{22}	p_{22}/δ_{22}
…	…	…	…
$(2,n)$	δ_{2n}	p_{2n}	p_{2n}/δ_{2n}
…	…	…	…
(m,n)	δ_{mn}	p_{mn}	p_{mn}/δ_{mn}

Input information：
1. The 3D model file.
2. The meshing and loading files.

Output information：
The stiffness matrix table.

Additional information：
The accuracy of the result is based on the meshing file.

CONSTRUCT THE PROCESS OF THE EFFECTIVE KNOWLEDGE RESOURCE PRECIPITATION

During the product life cycle, new knowledge resources are stored temperately in the cache knowledge resource database. When the design project ends, some of the new knowledge resources will be stored in the implicit knowledge resource database as the designers' experience and knowledge. More importantly, the others should be carefully standardized based on the standard format, so that, they can be inputted into the explicit knowledge resource database as the fixed assets of the enterprise. The standardization of the new knowledge resources is the main process of the effective knowledge resource precipitation, and it is also a heavy workload which that needs to be assigned among the departments in the enterprise.

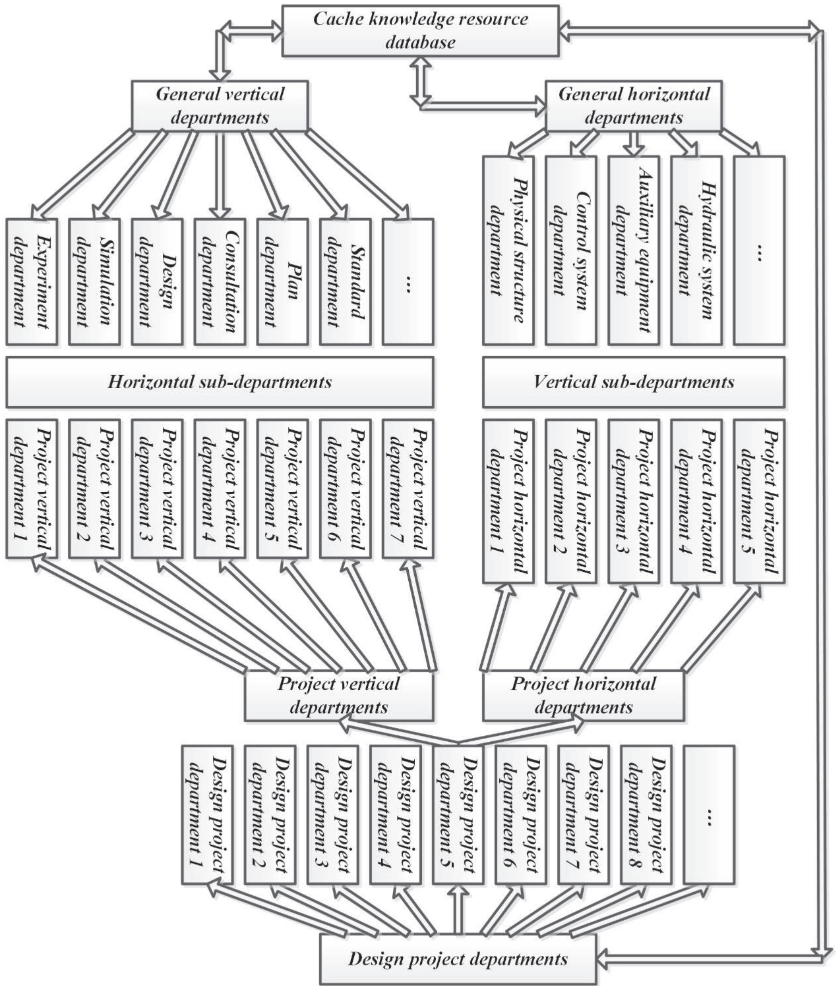

Figure. 4. Assign the standardizing workload of the new knowledge resources among the departments in the enterprise.

As shown in Figure 4, in an enterprise, there are three sets of departments, i.e.that is, general vertical departments, general horizontal departments, and design project departments. The first two sets serve all the design projects in the enterprise. The general vertical departments are classified based on the project process phases, like the standard department, the plan department, the consultation department, the design department, the simulation department, etcand so on. The general horizontal departments are classified based on the product components, like the hydraulic system department, the auxiliary equipment department, the control system department, the physical structure department, etcand so on. As for the last set, its departments just serve their own design project. When the design project ends, these departments should also be closed. These departments can also be classified into two kinds, that is, i.e. project vertical departments, and project horizontal departments. For a general or project vertical department, it may have many horizontal sub-departments. Meanwhile, for a general or project horizontal department, it may also have many vertical sub-departments.

Based on the above classification of the departments in an enterprise, a new knowledge resource stored in the cache knowledge resource database can be positioned accurately on a specific sub-department. Then, the designers in this sub-department should take the workload to standardize this new knowledge resource.

After the standardization, the new knowledge resources should go through a warehousing procedure, so that, they can finally deposit in the explicit knowledge resource database. This procedure facilitates the management of the explicit knowledge resource database, and it also makes the knowledge resource retrieval more convenient.

Figure 5 shows the warehousing procedure for the new knowledge resources. This procedure involves three kinds of departments, that is, i.e. vertical sub-departments, horizontal sub-departments, and the warehousing audit institution. At the beginning of a year, every vertical or horizontal sub-department should send the warehousing plan to the warehousing audit institution. After that, the submitted warehousing plan will be checked by the warehousing audit institution. If necessary, it can be sent back to its sub-department for modification and resubmission. When the warehousing plan is passed, the sub-department should start to prepare the warehousing work. At the end of the year, the sub-department should first list the standardized new knowledge resources. This list should be checked and then sent to the warehousing audit institution for the final check. If this list is passed, the new knowledge resources in this list will be stored in the explicit knowledge database.

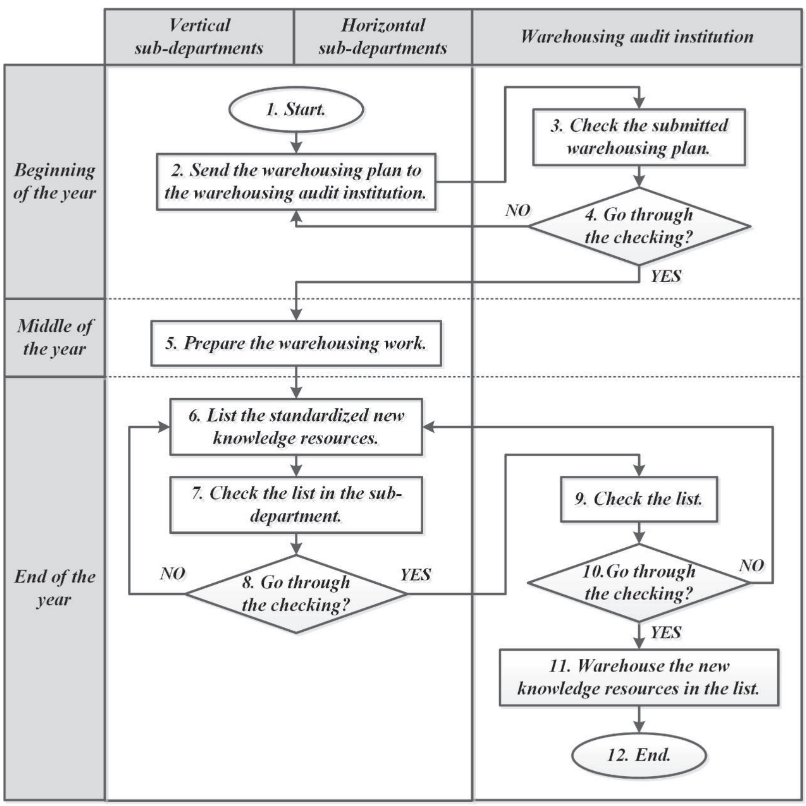

Figure 5. Warehousing procedure for the new knowledge resources.

CASE STUDY

With the proposed knowledge resource acquisition system, the existing knowledge resources can be reused effectively. Here, an internal combustion engine power unit was analyzed with different knowledge resources as a study case to illustrate the feasibility of the proposed system.

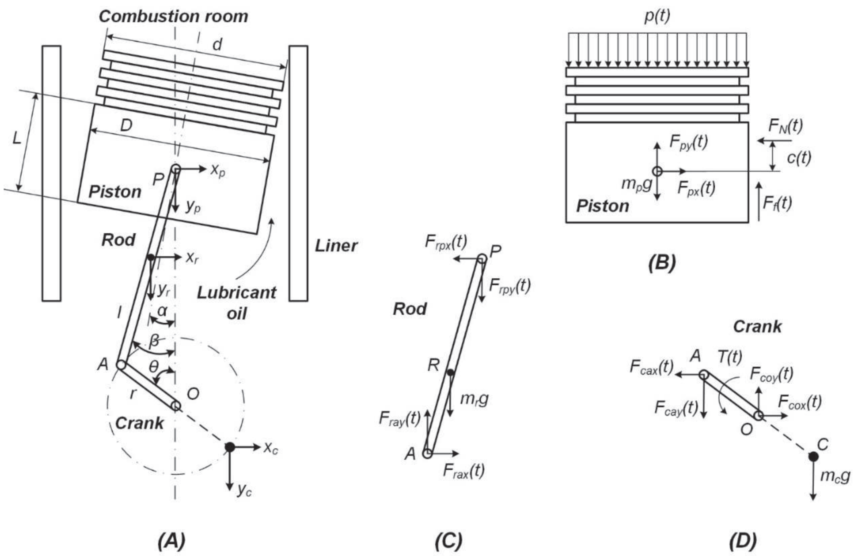

Figure 6. An internal combustion engine power unit.

As shown in Figure 6, a power unit consists of four parts, that is,i.e. piston, liner, rod, and crank. The piston moves up and down in the liner. It is stimulated by the gas in the combustion room. The lubricant oil in the gap between the piston and the liner separates the two surfaces from direct friction. So the piston is just effected affected by the radial force and the friction force from the lubricant oil, contact force and from the rod, pressure from the expanded gas, and the gravity. The arm of is. The rod is effected affected by the contact force and from the piston, the contact force and from the crank, and the gravity. As for the crank, it is effected affected by the contact force and from the rod, the contact force and from the spindle, torque from the flywheel, and the gravity.

The force balance equations of the piston, the rod, and the crank are shown as follows.

Piston:

$$\begin{cases} F_{px}(t) - F_N(t) = m_p\ddot{x}_p \\ \frac{1}{4}\pi d^2 p(t) + m_p g - F_{py}(t) - F_f(t) = m_p\ddot{y}_p \\ -F_N(t)c(t) - \frac{1}{2}DF_f(t) = I_p\ddot{\alpha} \end{cases} \tag{4}$$

Rod:

$$\begin{cases} F_{rax}(t) - F_{rpx}(t) = m_r\ddot{x}_r \\ F_{rpy}(t) - F_{ray}(t) + m_r g = m_r\ddot{y}_r \\ F_{rpy}(t)\overline{RP}sin\beta - F_{rpx}(t)\overline{RP}cos\beta + F_{ray}(t)\overline{AR}sin\beta - F_{rax}(t)\overline{AR}cos\beta = I_r\ddot{\beta} \end{cases} \tag{5}$$

Crank:

$$\begin{cases} F_{rox}(t) - F_{rax}(t) = m_c\ddot{x_c} \\ F_{ray}(t) - F_{roy}(t) + m_c g = m_c\ddot{y_c} \\ -F_{cax}(t)\overline{AC}cos\theta - F_{cay}(t)\overline{AC}sin\theta - T(t) + F_{cox}(t)\overline{OC}cos\theta - F_{coy}(t)\overline{OC}sin\theta = I_c\ddot{\theta} \end{cases} \quad (6)$$

In the equations, some variables cannot't be analyzed only by dynamics. Among them, $p(t)$ needs to be analyzed by gas thermodynamics, and $F_N(t)$ and $F_f(t)$ need to be analyzed by hydrodynamic lubrication. So, the designers can find out the corresponding knowledge resources through the acquisition system based on Table 2.

Table 2. The input and output of the required knowledge resources for the analysis of $p(t)$.

Input variables			**Output variables**		
Name	**Expression**	**Unit**	**Name**	**Expression**	**unit**
x_p	Horizontal movement of the piston	m	$p(t)$	Gas pressure	N/m^2
$\dot{x_p}$	Horizontal velocity of the piston	m/s			
β	Rotation angle of the rod	rad			
$\dot{\beta}$	Revolving speed of the rod	rad/s			
θ	Rotation angle of the crank	rad			
$\dot{\theta}$	Revolving speed of the crank	rad/s			

Table 3. The input and output of the required knowledge resources for the analysis of $F_N(t)$ and $F_f(t)$.

Input variables			**Output variables**		
Name	**Expression**	**Unit**	**Name**	**Expression**	**unit**
x_p	Horizontal movement of the piston	m	$F_N(t)$	Radial force from the oil film	N
$\dot{x_p}$	Horizontal velocity of the piston	m/s	$F_f(t)$	Friction force from the oil film	N
β	Rotation angle of the rod	rad			
$\dot{\beta}$	Revolving speed of the rod	rad/s			
θ	Rotation angle of the crank	rad			
$\dot{\theta}$	Revolving speed of the crank	rad/s			

DISCUSSION AND CONCLUSION

In this paper, a knowledge resource acquisition system was proposed for the product life cycle. In this system, a model was established for the knowledge resource flow in the product life cycle, and a classification was proposed for the new knowledge resources. Based on them, a standard format was proposed for the knowledge resources. Furthermore, the process of the effective knowledge resource precipitation was constructed with an assignment of the standardizing workload of the new knowledge resources and a warehousing procedure for the new knowledge resources. Finally, an internal combustion engine power unit was analyzed as a study case to illustrate the feasibility of the proposed system.

This proposed system can satisfy the basic requirement of knowledge resource acquisition. It can help an enterprise to standardize and precipitate the new knowledge resources obtained from the product life cycle. These precipitated knowledge resources actually become the fixed assets of the enterprise, so that, the explicit knowledge resource database of this enterprise can be constantly enriched in the daily running. This proposed system can also promote the using use efficiency of the existing knowledge resources. However, this proposed system still has some places waiting to be improved. For example, the explicit knowledge resource database should be classified more minutely, and a knowledge resource retrieval should also be added tointo this system. Most importantly, a process should be set up for the continuous improvement and update of the knowledge database as the information and knowledge change with the technological advances and organizational structural variations. All these problems will be taken into consideration in the further research.

ACKNOWLEDGEMENTS

The authors are grateful to the Key Project of State Key Laboratory of Mechanical System and Vibration (MSVZD201401), and the National Natural Science Foundation of China (51205247, 51575342).

REFERENCE

Camelo, D. M. & Mulet, E. 2010. A multi-relational and interactive model for supporting the design process in the conceptual phase. Automation in Construction, **19**(7): 964-974.

Chakrabarti, A. 2004. A new approach to structure sharing. Journal of Computing and Information Science in Engineering, **4**(1): 11-19.

Chen, B., Liu, J. & Xie, Y. 2016. An improved axiomatic design approach in distributed resource environment, Part 2: Algorithm for functional unit chain set generation. Procedia CIRP, 53: 44-49.

Chen, B. & Xie, Y. B. 2017. A complex-number-domain-based conceptual design synthesis for multidisciplinary products. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science., **231**(7): 1292-1307.

Chen, B. & Xie, Y. B. 2017. A computer-assisted automatic conceptual design system for the distributed multi-disciplinary resource environment. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, **231**(6): 1094-1112..

Chen, B. & Xie, Y. 2017. Functional knowledge integration of the design process. Science China Technological Sciences, **60**(2): 209-218.

Chen, B. & Xie, Y. 2017. A computational approach for the optimal conceptual design synthesis based on the distributed resource environment. International Journal of Production Research, **55**(20): 5881-5901.

Chen, B. & Xie, Y. B. 2017. A function unit integrating approach for the conceptual design synthesis in the distributed resource environment. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. Published online 1 February 2017. DOI: 10.1177/0954406217692008.

Chen, W. Gao, F., Meng, X., Chen, B., & Ren, A. 2016. W2P: A high-power integrated generation unit for offshore wind power and ocean wave energy. Ocean Engineering, 128: 41-47.

Chen, W. Gao, F., Meng, X., & Fu, J. 2016. Design of the wave energy converter array to achieve constructive effects. Ocean Engineering, 124: 13-20.

Chen, W. Gao, F., Meng, X., Ren, A., & Zhou, S. 2017. An offshore hydraulic wind turbine generator with variable-diameter rotor: Design, modeling and experiment. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, **231**(2): 521-532.

Chen, W., Meng, X. & Gao, F. 2016. The principle of a three-DOF mechanism for wave energy absorption. In: ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering. Busan, South Korea: American Society of Mechanical Engineers, pp. V006T09A030-V006T09A030.

Gero, J. S. 1990. Design prototypes: a knowledge representation schema for design. AI magazine, **11**(4): 26-36.

Gero, J. S. & Kannengiesser, U. 2004. The situated function-behaviour-structure framework. Design studies, **25**(4): 373-391.

Helms, B., Shea, K., & Hoisl, F. 2009. A framework for computational design synthesis based on graph-grammars and function-behavior-structure. In: ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. San Diego, California, USA: American Society of Mechanical Engineers, pp. 841-851.

Komoto, H., & Tomiyama, T. 2012. A framework for computer-aided conceptual design and its application to system architecting of mechatronics products. Computer-Aided Design, **44**(10): 931-946.

Kurtoglu, T., Swantner, A. & Campbell, M. I. 2010. Automating the conceptual design process: "From black box to component selection". Artificial Intelligence for Engineering Design, Analysis and Manufacturing, **24**(01): 49-62.

Liu, J., Chen, B. & Xie, Y. 2016. An improved axiomatic design approach in distributed resource environment, Part 1: Toward functional requirements to design parameters transformation. Procedia CIRP, 53: 35-43.

Pahl, G., & Beitz, W. 1996. Engineering design: a systematic approach. 3rd ed. Springer-Verlag, New York.

Qiu, P., Sun, R., Gao, G., Chen, B., Zhang, C., Yin, T., Zhang, J., Fang, S. & Cui, D. 2015. Hydrothermal targeted-explosion synthesis of hollow/porous upconversion nano- and microcrystals with potential for luminescent displays and biological imaging. ChemNanoMat, **1**(2): 128-134.

Qiu, P., Sun, R., Gao, G., Yin, T., Shen, Y., Chen, B., Wang, K., Zhang, C., Qian, X. & Cui, D. 2015. Crystal cell oriented-rotation triggered phase transition of porous upconversion nanocrystals synthesis in hydrothermal system. Journal of Materials Chemistry B, **3**(19): 3948-3958.

Qiu, P., Sun, R., Gao, G., Zhang, C., Chen, B., Yan, N., Yin, T., Liu, Y., Zhang, J., Yang, Y. & Cui, D. 2015. An anion-induced hydrothermal oriented-explosive strategy for the synthesis of porous upconversion nanocrystals. Theranostics, **5**(5): 456-468.

Schmidt, L. C., Shetty, H. & Chase, S. C. 2000. A graph grammar approach for structure synthesis of mechanisms. Journal of Mechanical Design, **122**(4): 371-376.

Suh, N. P. 2001. Axiomatic design: Advances and applications. Oxford University Press, New York.

Welch, R. V. & Dixon, J. R. 1994. Guiding conceptual design through behavioral reasoning. Research in Engineering Design, **6**(3): 169-188.

Submitted: 08/04/2016
Revised : 29/12/2016
Accepted : 05/01/2017