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Managing Coordination Complexity in the Remanufacturing of Aircraft Engines

Abstract The complexity of communication and coordination stemming from teams responsible for adjusting interdependent parameters of components is a fundamental feature in the aircraft engine remanufacturing engineering project. To manage coordination complexity, the features of the remanufacturing process of aircraft engine are analyzed and a systematic method is presented to measure and optimize the dependency between coupled components. Furthermore, quantitative models are built based on Design Structure Matrix (DSM) models to measure dependency strengths related to the parameter features of the components. Also, a two-stage DSM clustering criteria is used to reduce the complexity of an organization. An industrial example is provided to illustrate the proposed models. The results showed that the proposed approach can reduce total coordination complexity.

Keywords: remanufacturing engineering project, aircraft engine, coordination complexity, organization optimization, design structure matrix (DSM)

1 Introduction

The aircraft engine maintenance can be classified into an organizational level, intermediate level and depot level according to the depth, width and location of aircraft maintenance. The development process of aircraft engine maintenance and remanufacturing technology is different from that of the general new product, in which the former's final goal is to establish and industrialize the application of technology instead of developing a physical product. Another difference between the operation processes of engine maintenance and remanufacture and that of the general produce is that the former focuses on the life-cycle and the damaged engines or parts, and it is a reverse process to restore the performances of the damaged parts or the engine with integrated application of maintenance and remanufacturing technology (Xiang, 2013).

Remanufacturing processes of complex systems include managing a great number of interfaces between organizations and activities. The remanufacturing process is a kind of product development process. Unlike the ordinary manufacturing process, the product development process can be described as "creative," "innovative" or "iterative," involving a complex web of interactions for information exchange (Eppinger, 2001).

To be competitive, firms that design and develop complex products seek to optimize the organization structure of their projects to reduce the management and coordination complexity, which is a fundamental feature of product development process. The concurrent engineering requires extra time for coordination while reducing duration of a project (Yang & Tang, 2014). According to our field studies, reducing the complexity of communication and coordination is the main reason for many firms to adjust their organization architecture (Eppinger & Browning, 2012).

The Design Structure Matrix (DSM) method proposed by Steward (1981) is a powerful network modeling tool to represent the elements comprising a system and their interactions, and thus highlights the complexity of a system, including *process architecture, product architecture* and *organization architecture* (Eppinger & Browning, 2012; Yassine, Chidiac, & Osman, 2013). The most important part for establishing the system is the interface. Although each component of the system focuses on particular interaction (e.g., communication, information flow and input-to-output relationships), inherent relationship exists in the different components. DSM can be utilized to identify clusters, i.e., potentially good modules/groups, and their interfaces in complex system. Clustering technique has been widely recognized as one of the important ways to manage complexity. The major benefits of modularity include reduced complexity, increased efficiency and reduced cost (Eppinger & Browning,

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2012). Measuring the interaction strength between elements is the first step for clustering (Yang, Kherbachi, Hong, & Shan, 2015). DSM can capture not only the existence of an interaction, but also the interaction strength. Thus, how to measure the interaction strength is an important issue for clustering a DSM.

Therefore, in order to reduce management complexity and optimize organization architecture in complex remanufacturing projects, a numerical Design Structure Matrix (DSM) is presented for analyzing the dependency strength and clustering organizational units in the aircraft engine remanufacturing engineering project.

2 The characteristics of the remanufacturing process of the aircraft engines

2.1 The difference between repair, restoration and remanufacturing

Repair refers to a technical method for keeping products in a good technical state and operating normally. The objects of repair are the products with defects and the product requiring heavy maintenance. The repair process mainly focuses on replacing or repairing individual components. Usually, the facilities and technology used while repairing are and cannot establish batch production. Most of the repaired products are not comparable to new products from the perspectives of quality and performance.

Restoration means that repairing and restoring the damaged parts by taking some technical methods when products lose their partial structure or functions. The objects of restoration are the damaged parts which can still work when restored and conventional facilities and technology are used.

Remanufacturing is an advanced stage of maintenance which involves a series of technical measures or engineering activities and the product life cycle design and management is used as a guide (Xiang, 2013). With the aims of high quality, efficiency, energy saving and environmental protection, the remanufacturing process restores or transforms the discarded products through advanced technology and the industrialization of production, and make the quality and performance of the produce even better than those of new products. Remanufacturing is an important approach to realize the classifying maintenance, depth maintenance, scientific maintenance and preventive maintenance in depot level maintenance. The main process of restoration and remanufacturing is shown in *Figure 1* (Xiang, 2013).

In general, remanufacturing only needs 20%–25% of the energy and 10%–15% of material consuming compared with manufacturing new products. It can lower the cost and reduce waste remarkably (Xiang, 2013)

2.2 The characteristics of the remanufacturing process of the aircraft engine

(1) Aircraft engine is a product with high reliability, high risk and high investment which leads to high requirement of remanufacturing engineering

The high reliability of the aircraft engines means the ability to complete specific functions under stipulated conditions within specific time period. The aircraft engine is a power machinery in which gas in combustion works under high pressure and this complicated heat rotating machinery is developed on the basis of aerothermodynamics, combustion, structural mechanics and automation technology. Integrated by tens of thousands of precision

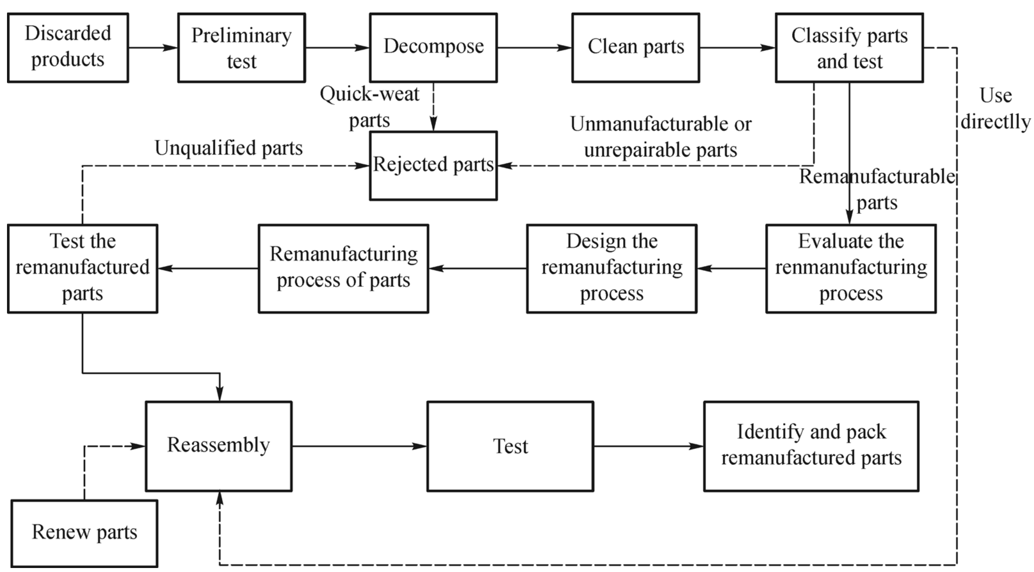


Figure 1. The main process of restoration and remanufacturing process.

components in a strictly limited space, the aircraft engine should not only fulfill many special requirements such as the performance, operational suitability and, but also work longer and more reliable under severe conditions, including tight pressure, high temperature, fast rotating speed and stress change in a wide range. Therefore, the requirement for reliability of aircraft engine is higher than that of general mechanical products. Also, higher requirements of the remanufacturing process are needed (Xiang, 2013).

Aircraft engine is risky On one hand, during engine repairing process, the probability of accidents will be higher due to risk factors such as the engine itself, repair technology, crafts, spare parts, men and the environment. On the other hand, any tiny risk of accidents may cause huge losses to aircraft engine and even pose threats to pilots' lives and bring serious losses for national security as well. The high risk of aircraft engine raises higher requirements for remanufacturing engineering.

Compared with aircraft engine manufacturing, remanufacturing can cut the cost significantly. The remanufacturing process includes the preparation, the application of advanced technology, the reliability after being remanufactured, and quality test. During this process, many expensive processing equipment, testing instruments, and assessment and verification devices are used. For instance, an advanced thermal barrier coatings processing equipment is worth tens of millions of RMB and a thermo-mechanical fatigue test will cost tens of thousands of RMB. Huge investment raises higher demands on remanufacturing engineering (Xiang, 2013).

(2) Higher requirements for remanufacturing engineering resulted from restoration and remanufacturing of critical components

The manufacturing of critical components of aircraft engine is a high-tech and complicated process with high added value. Remanufacturing these components will have higher commands (demands) than remanufacturing general electromechanical products. It has a great technical difficulty and special restrictions to restore and remanufacture critical components which make these components recover, keep and even improve their technical performance. This process must use the high technology which is more advanced than that of the original product manufacturing. It needs a system integration innovation and has interdisciplinary characteristics. Technology, staff, facilities and other aspects propose higher requirements to aircraft engine remanufacturing engineering (Xiang, 2013).

Remanufacturing is a batch and specific production process for restoring discarded components. Critical components in aircraft engine, such as compressor rotor blades and turbine rotor blades, may have a variety of defects and failures easily after working for a long-term repeatedly under severe conditions of high temperature, high pressure, high speed and high load. Therefore, critical components are the main objects of aircraft engine's restoration and remanufacturing.

3 Clustering optimization method based on Design Structure Matrix (DSM)

3.1 Measuring the dependency strength in DSM

Remanufacturing projects of aircraft engines are generally complex and involve highly interdependent collaborative activities carried out by multiple teams and individuals. Therefore, efficient communication is necessary to increase the performance of projects. DSM models can be utilized to measure the dependency strength between elements in complex systems. It has been used to map and decompose large complex systems into appropriate sub-systems on the basis of a variety of parameter interactions.

DSM is a value stream analysis tool to analyze and optimize the manufacturing process here. DSM can describe the information transfer between activities (or the communication between organizational units, energy transfer between the components of the product). DSM can be used to easily analyze the value stream of complicated systems. Moreover, it can improve information flow, optimize task sequencing and reduce rework. As shown in *Figure 2*, a symbol "×"represents the information flow from one stream to another one, which is dependence or coupling relationship. The symbol "×" above the diagonal represents the information flow sequential transmission which means information transfer from upstream activities to downstream activities. Instead, the symbol "×" represents the information flow feedback that means information transfer from downstream activities to upstream activities. Feedback usually will cause rework. The size of the symbol "×" stands for the strength of coupling relationship between activities.

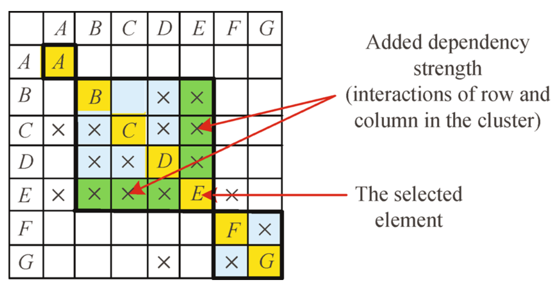


Figure 2. DSM and the added dependency strength.

Measuring the dependencies between the elements in DSM is one of the decisive factors for clustering analysis. To simplify the clustering process, initially all interaction strengths were weighted equally (i.e., binary interaction strength). Thebeau (2001) defined a strong interaction as an interaction that was highly important, critical to operation, but this method is qualitative and dependent on the preference of managers. Thus, simple binary interaction strength is replaced by some weighted rating scales for rating interaction between elements in DSM.

To characterize assembly relationship and energy relationship in the remanufacturing process, a new dependency rating scheme is presented here to measure *the integrated coordinative dependency strength* (ICDS) between teams using DSM. Thus, bigger coordination drivers meaning stronger dependency relationship of communication and coordination will be caused between parts I and j. $DS_{AR}(i,j)$ and $DS_{ER}(i,j)$ are the *dependency strength* resulted from assemble relationship and energy relationship in the remanufacturing process respectively. So, the ICDS can be calculated with Eq. (1):

$$ICDS(i,j) = \omega_1 DS_{AR}(i,j) + \omega_2 DS_{ER}(i,j) \quad (1)$$

where ω_1 and ω_2 are weight coefficients, $\omega_1 + \omega_2 = 1$.

The technical communication strength related to the assembly relationship and the energy relationship is a dominant factor. If the technical communication resulted from product feature does not exist, any other factor will not take a part in measuring ICDS.

3.2 Clustering optimization criterion

After interaction strengths between teams are quantified, the next step is to cluster elements into chunks. A cluster or a module is commonly defined as an independent "*chunk"* that is highly coupled within, but only loosely coupled to the rest of the system. Several researchers have explored clustering methods and integrative mechanisms for organization. McCord and Eppinger (1993) developed the first application of DSM for the integration and coordination of cross-functional teams of engine development in General Motors (Eppinger & Browning, 2012). Browning (1999) studied the integrative mechanisms among cross-functional development teams. Yang, Yao, Lu, and Zhang (2014) studied an Overlapping-based DSM for measuring interaction strength and clustering analysis in product development project.

Coordination complexity can be reduced if teams are clustered such that the interactions predominately occur within group, rather than between groups. Therefore, the first criterion is that the interaction strength is maximized internally within group. In other words (*Figure 3*), most, if not all, of the teams assigned to each activity with strong internal interaction strength are grouped in one cluster and external interaction strength between clusters are weak (Yang & Tang, 2014).

ADS (Added dependency strength) can be calculated with Eq. (2):

$$max\ ADS\ (cluster_k) = \frac{\left(\sum_{j=n_k}^{m_k-1} ICDS(j,m_k) + \sum_{k=n_k}^{m_k} ICDS(m_k,k)\right)^{\gamma}}{2(cl_k-1)} \quad (2)$$

where cl_k is the size of cluster k, n_k, and m_k are the indices of the first and the last element in cluster k, respectively, γ is a penalty coefficient.

To reduce coordination complexity, the second-stage criterion of clustering is the minimization of *Total Coordination Cost*, including both *Internal Coordination Cost* (ICC) and *External Coordination Cost* (ECC). ICC refers to the cost resulting from coordination and communication inside a cluster. It is affected by *technical coordination frequency* (TCF) inside the cluster, ICDS, number of teams in one cluster and so on. The TCF inside cluster k and ICC can be calculated with Eqs. (3) and (4) respectively.

$$TCF(cl_k) = \varphi_0 \exp\left\{-\frac{1}{(\max((cl_k-(cl_0-1)),1))^{\eta}}\right\} \quad (3)$$

$$ICC = \sum_{k=1}^{N_C}\left(\left(\sum_{i=n_k}^{m_k}\sum_{j=n_k}^{m_k} ICDS(i,j)\right) \times TCF(cl_k)\right) \quad i \neq j \quad (4)$$

where φ_0 represents the inherent uncertainty, cl_0 is the ideal size of a cluster for a project, N_C is the number of teams in a cluster, cl_k is the maximum number of clusters k, η is a penalty coefficient, N_C is the number of clusters in the DSM.

The main factors that affect ECC include TCF between teams outside the cluster, ICDS, the size of clusters. The TCF and the total ECC can be calculated with Eqs. (5) and (6).

$$TCF(cell\_out) = \varphi_0 \exp\left(-\frac{1}{(\max((cell\_out-(cell\_out_0-1)),1))^{\lambda}}\right) \quad (5)$$

$$ECC = \sum_{k=1}^{N_C}((\sum_{i=n_k}^{m_k}\left(\sum_{j=1}^{n_k\text{-}1} ICDS(i,j) + \sum_{j=m_k+1}^{N} ICDS(i,j)\right) \times TCF(cell\_out))) \quad (6)$$

where $cell\_out$ is the total number of cells (coordination dependency) outside the cluster, $cell\_out_0$ is the ideal number of cells outside the cluster, λ is a penalty coefficient.

Hence, the second stage clustering objective is to minimize the weighted *Total Coordination Cost* (TCC) including ICC and ECC.

$$\text{Min}: TCC = \nu_1 \times ICC + \nu_2 \times ECC \quad (7)$$

$$\text{Subject to}: \ cl_k \leqslant cl_0$$

where ν_1 and ν_2 are weight coefficients, $\nu_1 + \nu_2 = 1$.

4 Case studies

An industrial example is utilized to verify the proposed concepts and model. *Figure 3* shows the aircraft engine remanufacturing process which involves lots of interdependent parameters which are needed adjustment. Adjusting or repairing some components to make one parameter qualified may cause other parameter changes of the components, and it makes troubleshooting more difficult. In the remanufacturing process, if the individual (or team) related to this process does not coordinate and communicate effectively and the information does not exchange fully and timely, the working upstream process may rework which influences the delivery cycle time of the products.

Thus, clearly identifying and measuring the dependencies between components in the remanufacturing process and regrouping the individual related to every component, and then keeping the close communication occurring within a relatively small range are critical to reduce management complication and the risk of rework. In the aircraft engine remanufacturing process, the dependencies between components are mainly two kinds: assembly relationship and energy relationship. Assembly relationship means the relationship between physical interfaces, while energy relationship involves the dependency relationship of pressure, rate of flow, angular displacement and other dependencies. Therefore, the energy relationship is complicated.

The adjusting parameters of the product are coupled and interdependent with each other. There are four parameters involved in the product adjusting process (i.e., flow 1, flow 2, displacement and pressure). When a product is being adjusted or repaired, certain adjusting or repairing work will determine an engine performance parameter. The change of this parameter may lead to changes in the performance parameters which are affected by other activities and the whole remanufacturing process and adjusting process are highly coupled. As a result, the repairing and troubleshooting are more difficult, and the assembly and adjusting cycle time is more unpredictable.

Therefore, the objective of clustering optimization of the aircraft engine remanufacturing process is: putting the relative components together for checking and repairing malfunction so as to decrease the communication complexity, and finally increasing the first-pass yield (FPY), reduce rework and cycle time.

This project contains 15 components with each performing a unique team and activity. *Figure 4* (a) shows the original numerical DSM, in which each dot represents integrated coordinative dependency strength (ICDS) and is calculated by Eq. (1). Here, the larger dot represents stronger communication. The original DSM shows a lot of interaction marks, which significantly increase the complexity of management. Due to the long distance of the feedback, the communication of which becomes stronger, which means higher strength feedback communications will delay the remanufacture cycle time. Here the original organization is optimized based on DSM models to make the communication between the individual components more effective.

Using Eqs. (2)–(7), the DSM is optimized. *Figure* 4 (b) shows that the clustered numerical DSM has been decomposed into small groups. In the clustered DSM, teams that have strong interaction are clustered. As a result, teams [G,H,J,D,L], [D,L,B,K,N], [N,F,I,P] and [I,P,A,C,E, M] are grouped to four different clusters which are responsible for four kinds of adjustments of the parameters (i.e., flow 1, flow 1, flow 1, flow 2, displacement and pressure). Here, components D, L, N, I and P are overlapping components. Because communication occurs in a team, the management complexity is reduced significantly after clustering. Meanwhile, the reorganized teams will also reduce the human resource cost and material cost of rework. Another result of the numerical clustering is that the DSM elements which have strong dependency with others in the row or column are integrated in one group.

5 Conclusions

Coordination complexity is a fundamental feature of the remanufacturing processes. First, the features of the remanufacturing process of aircraft engine are analyzed. Then, the numeric DSMs are presented to measure interaction strength between teams in remanufacturing processes and to reduce the remanufacturing processes for reducing management complexity through clustering Optimization. The optimized DSM indicates that strong communication occurs within a team reduces the feedback distance. In practice, the project manager can utilize the models to optimize teams which take responsible for coupled components in the adjustment process of the remanufacturing engineering project to reduce coordination complexity.

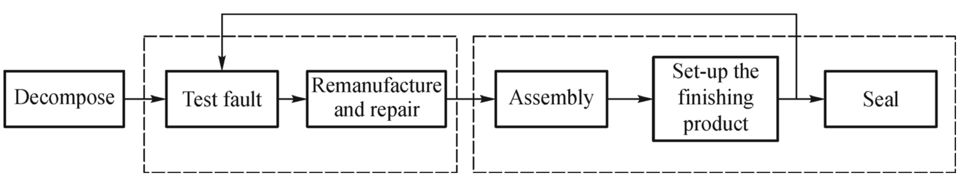
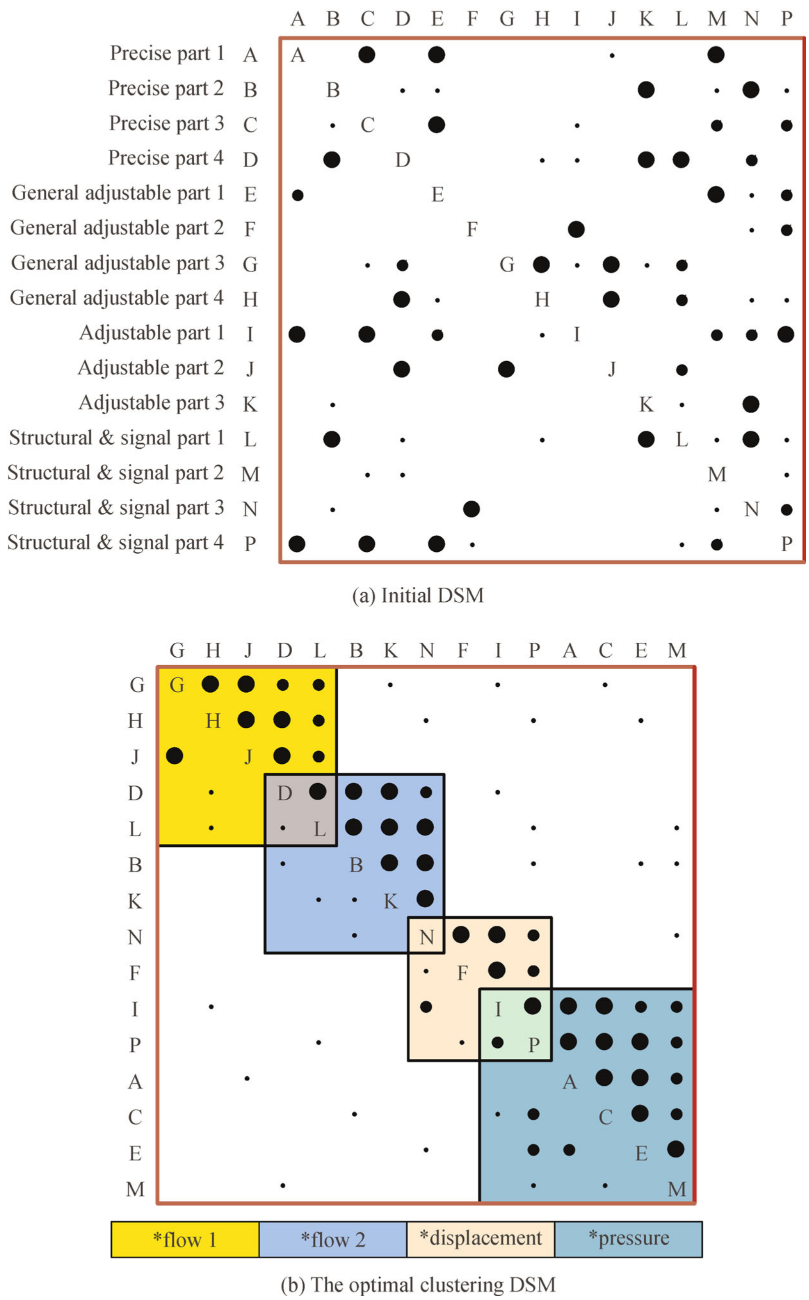


Figure 3. The aircraft engine remanufacturing process.



(a) Initial DSM

(b) The optimal clustering DSM

Figure 4. The remanufacturing process value stream analysis based on DSM.

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