Proceedings of the 9th WSEAS International Conference on Applied Mathematics, Istanbul, Turkey, May 27-29, 2006 (pp400-405)

Adaptive Control Architecture-based Supply Chain Management (SCM)

PYOUNG YOL JANG
Science & Technology Policy Institute (STEPI)
26th Fl., Specialty Construction Center 395-70, Shindaebang-dong, Seoul 157-714
REPUBLIC OF KOREA
http://www.stepi.re.kr/jangpy

Abstract: The supply chain consists of various subsystems such as manufacturing systems, delivery systems, distribution systems, and transport systems. In particular, the manufacturing system plays an essential role but it is so complex that it is hard to predict and optimize the global supply chain. To optimize and execute the manufacturing system, the shop floor control system (SFCS) has been developed and various control architectures have been proposed. In spite of their benefits, it is difficult to cope with the changing demands of process plans and parts in the supply chain, due to the lack of self-adjustment to the manufacturing environment and guarantee global optimization. The objective of the paper is to propose the conceptual framework of a democratic control architecture that overcomes the defects of the previous control architectures for the efficient supply chain management. The solution to the new control architecture can be found in political systems. Modern nations develop a political system so as to mediate conflicts among people, and to accommodate nation's global benefits. Similarly, a SFCS should also resolve conflicts among controllers and maximize shop floor's overall benefits. With the support of proposed framework high-performance and adaptability to the dynamic change of shop environments can be simultaneously achieved in shop floor control to cope with the ceaseless fluctuations in the supply chain.

Keywords: *Supply Chain Management (SCM), Democratic Control Architecture, Manufacturing, Adaptation*

1 Introduction

The supply chain consists of various subsystems such as manufacturing systems, delivery systems, distribution systems, and transport systems. In particular, the manufacturing system is so complex that it is hard to predict and optimize the global supply chain. Moreover, modern manufacturing industry faces new challenges to survive in competition, such as shorter lead times, higher product quality, various customer demands, and lower manufacturing cost. Further, continuous and unexpected changes from the supply chain become key obstacles in success. In order to cope with these challenges, a shop floor control system (SFCS) as a key component of production systems, must be flexible and reconfigurable.

Neither hierarchical nor heterarchical control architecture for shop floor control is structured to cope sufficiently with these challenges [1][2]. The former cannot handle the unpredictable changes of manufacturing environment adequately due to its stiffness. The latter cannot guarantee globally optimized decision-making in spite of its adaptability to environment. Therefore, a new control architecture has yet to appear to guarantee both global optimization and self-adaptation to the changing environment.

The objective of the paper is to propose a conceptual framework of a new control architecture, democratic control architecture for the efficient supply chain management. The detailed objectives are: 1) to define the framework of democratic control architecture, 2) to propose the roles and relationships of the three powers-administration, legislation and judicature, and 3) to illustrate the applications of the proposed control architecture to prototype shop floors in the supply chain

The clue to the democratic control architecture can be found in political systems. Various political systems, such as democracy and limited monarchy, play important roles in mediating conflicts among people and accommodating nation's global benefits. Similarly, a SFCS should resolve conflicts among controllers and maximize shop floor's overall performance. Some similarities between the two systems are depicted in Table 1. The democratic political system gives rise to the concept of "democratic control architecture"(DCA) for shop floor control.

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Table 1. Political system vs. control architecture

The number of sovereigns		Political system	Conventional control architecture	New control architecture
1		Monarchy	Central control Hierarchical control Hybrid control	
Minority		Aristocracy		
Majority	Direct	Ancient Greek Polity	Heterarchical control	
	Indirect	Democracy		***Democratic control***

To reflect the nature of democracy, the democratic control architecture has the two essential characteristics: respective independence of the three powers in control andthe evaluation and election of controllers (corresponding to politicians). First, various conflicts and issues occurring in the shop floor can be resolved by the three powers elected from the controllers. Second, each controller should be evaluated in terms of its performance and achievement, which initiates countermeasures (election) against the low-performed controllers.

The following assumptions and conditions are made as part of the paper. 1) Parts enter the shop with process plans represented as an AND/OR graph form. 2) A shop consists of several kinds of resources, such as processing machines, inspection machines, robots, conveyors, etc. 3) A communication protocol has been defined.

2 Related Work

In the open literature, the four main control architectures – centralized control, hierarchical control, hybrid control, and heterarchical control architectures - have been extensively researched as shown in Figure 1 [3]. In the centralized control architecture, one controller manages the entire stock of equipment and maintains global information to record the activities of the whole SFCS. The shortcomings of the centralized control architecture resulted in the development of the hierarchical control architecture, in which a top-down structure strictly defines the system modules and their functionalities [2]. Several prototypes have been developed such as AMRF (recently RCS and MSI) and COSIMA [1][4]. However, it has difficulties with dealing with dynamic adaptive control and difficult of making future unforeseen modifications. Modified hierarchical control architecture is based on the hierarchical control architecture, but allows limited coordination among controllers to carry out a sequence of activities initiated by a command from the supervisory controller. However, the rigid master/slave relationship is not relieved. Heterarchical control architecture is composed of distributed autonomous equipment controllers communicating with each other without hierarchy[5] [6].

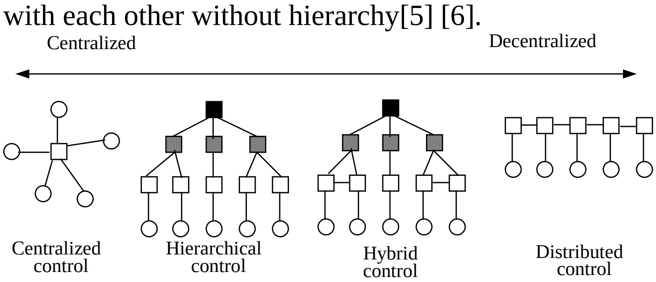

Figure 1. Conventional control architectures

3 Framework

If a supervisor has all the powers, the unreasonable or mistaken commands/decisions cannot be rejected or corrected by other controllers, which may result in low-performance of the SFCS. Hence, all the controllers must be able to hold each other in check. To this end, the three independent powers are constituted - administration, legislation and judicature - by referring to the political systems. They keep a respective independence instead of a master/slave relationship. The conceptual framework for the respective independence of the democratic control architecture is shown in Figure 2.

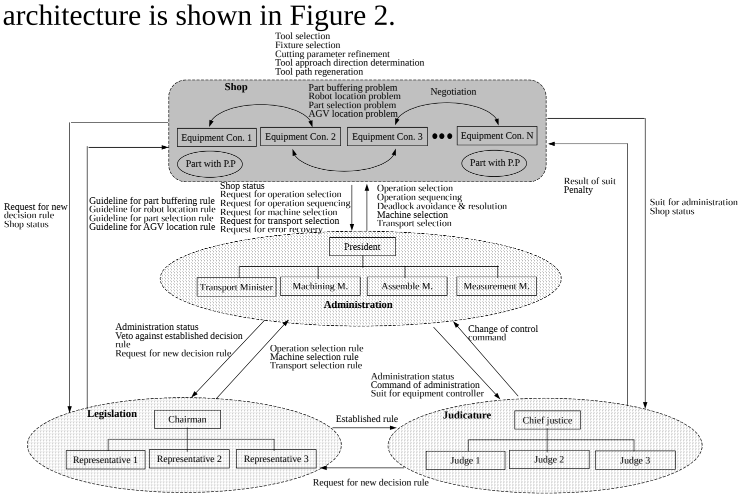

Figure 2. Independent roles of the three powers

Decision-making problems occurring in a shop floor are classified into the four groups according to how they can be resolved: 1) device-specific problems, 2) minor problems, 3) executive problems, and 4) major problems as shown in Figure 3. First, autonomy given to each controller is used to resolve several device-specific activities, such as tool selection, fixture selection, cutting parameter refinement, tool approach direction determination, and tool path regeneration. The device-specific problems are solved by an equipment controller itself without negotiation. Second, cooperation among equipment controllers can be utilized to resolve some decision-making problems, such as part buffering problem, robot location problem, part selection problem, and AGV location problem. Third, some problems should be solved not by the equipment controllers themselves but by the external higher levels (so called the three powers) of equipment controllers to reflect the shop floor's entire point of view. In particular, the executive problems concern the operation of the shop floor, whose rules and solutions are managed by the legislation, such as operation sequencing, deadlock avoidance, deadlock recovery, and error recovery. Fourth, the major problems are fundamental basis in control and have the highest degree of importance, whose rules and solutions are managed by the legislation, such as operation selection, machine selection, and transport selection. They are referred by the administration and judicature, and are considered as the highest priority over the others. The problems in each group can be managed and transferred to the higher or lower level of a group according to the shop environment by the legislation.

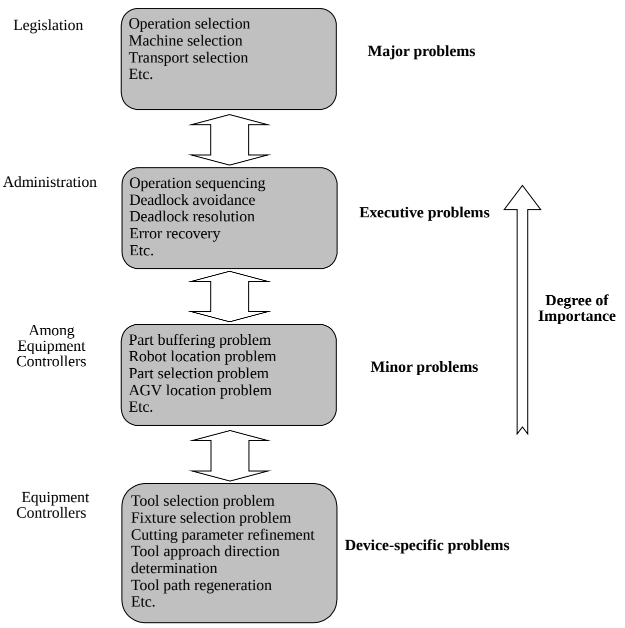

Figure 3. Problems dealt with the SFCS

The administration keeps monitoring shop floor status to resolve conflicts among equipment controllers. The equipment controller that receives an unreasonable command from the administration can bring a suit. Similarly, the administration can bring a suit against the equipment controllers that do not obey. The legislation makes a new decision rule for the problems if requested by equipment controllers, the administration, and the judicature and provides the equipment controllers with a guideline to resolve minor problems. The judicature makes a judicial decision upon the suit based on the established rule by the legislation.

Every equipment controller consists of the three modules, the intra-module that manages local operations, the inter-module that performs interactions among other controllers, and the three powers module that becomes a candidate for one of the three powers as shown in Figure 4. The inter- and intra-modules are further decomposed into the three functions: decision-making for conflict resolution, monitoring for checking order progress, and execution of planned and scheduled tasks. The three powers become one of president, minister, representative, and judge.

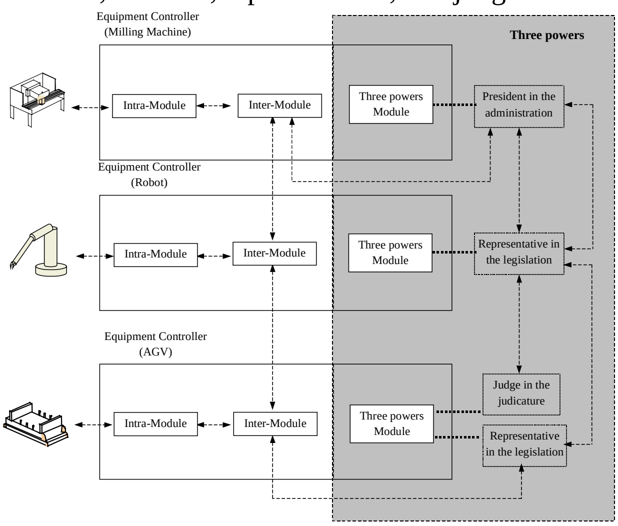

Figure 4. Configuration of an equipment controller

4 Structure of the Administration

The administration manages and coordinates the activities of equipment controllers. The top controller of the administration is called as the "*President*", which is responsible for managing all the controllers and coordinating with the legislation and judicature. It has a three-level hierarchy, in which every equipment controller is located at the bottom level, as shown in Figure 5. The middle level called as the "Minister" can be classified in terms of a functional aspect, such as transport, assembly, machining, and measurement. In order to construct an initial administration structure, the equipment controller with an average control-characteristic parameter (may be about 0.5) becomes a president. Similarly, the ministers are selected. An exemplary administration construction is shown in Figure 5.

While there is a strict hierarchical relationship between the president and ministers, there are no master/slave relationships but is loose hierarchy between the equipment controller and ministers. In other words, the equipment controllers reports their status and request solutions for a specific problems but they can ignore the provided solutions in such cases as follows: 1) The changes of a shop floor: Due to the changes of a shop floor environment such as the changes of resources and the change of a shop layout, the provided solutions can be out-dated or not proper for current situations. 2) The disturbances of a shop floor: Due to the sudden disturbances such as resource failure and cutting tool breakage, the existing rule and provided solutions cannot be applied. 3) New parts with new process plans: When new parts with new process plans enter the shop, the existing rule and provided solutions may not be applied. 4) Excessive decisions: The equipment controllers can consider the provided solutions as excessive decisions.

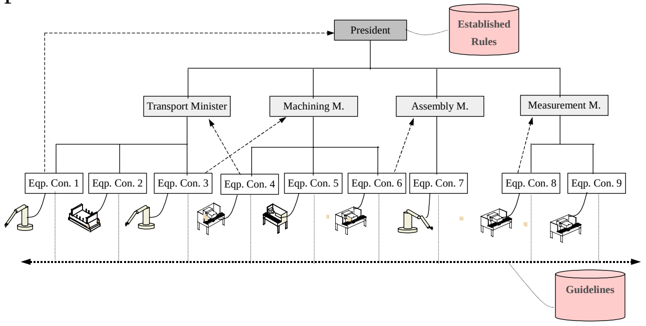

Figure 5. Structuring the administration

When the president or ministers receives the requests from equipment controllers, they make a decision based on the established rules by the legislation or the administration's own rules according to the types of problems. The minor problems are resolved by negotiation among equipment controllers and they can refer the guideline established by the legislation in such cases as follows: 1) When the negotiations among equipment controllers are not smoothly performed. 2) When the device-specific problems cannot be resolved by an equipment controller itself.

In normal situation the administration just responds to the request and keeps monitoring shop floor status, however, it intervenes among the equipment controllers to maximize shop floor's overall benefits in such cases as follows: 1) Deadlock avoidance: To avoid deadlock situation in a shop floor, 2) Deadlock resolution: To resolve deadlock situation in a shop floor, 3) Error recovery: To recover the errors in a shop floor such as device failure and emergency situation, and 4) Local optimum: To accommodate shop floor's global benefits instead of the local optimum decided by the negotiation among the equipment controllers

In above cases, the administration forces the equipment controllers to stop the next operations and gives necessary orders.

Since there are no master/slave relationships between the president/ministers and the equipment controllers, it can bring about conflicts. Therefore it is necessary to provide the mechanism to resolve these conflicts. In the DCA, these conflicts should be resolved by the judicature, and the types of conflicts can be categorized as follows: 1)Global optimum vs. Local optimum: The administration considers the global optimum while the equipment controller considers equipment's local optimum. 2) The changes of a shop floor: Since the rules and decisions established by the legislation or the administration may not reflect promptly the change of a shop layout, the provided solutions can be out-dated or not proper for current situation. 3) The disturbances of a shop floor: Since the rules and decisions established by the legislation or the administration may not reflect promptly the sudden disturbances, the existing rule and provided solutions cannot be applied. 4) New parts with new process plans: In case of new parts with new process plans, the existing rules may not be applied.

However, the commands from administration based on the executive and major problems are not final decisions, and hence the equipment controllers can ignore the provided solutions in case of changes and disturbances in the shop floor may force.

5 Structure of the Legislation

The legislation creates and modifies the rules used for decision-making. The top level of the legislation is called the "*Chairman*", under which there are a few representatives. The chairman coordinates the activities among representatives. The number of representatives depends on the shop environment.

Each representative performs the roles via the negotiation procedure based on the pre-constructed knowledge base which is periodically updated. A certain number of representatives can constitute a committee, such as machining committee and transport committee corresponding to the ministers of the administration to efficiently establish and change rules as shown in Figure 6. Initially, the representatives with an average control-characteristic parameter are selected from the equipment controllers. An exemplary administration construction is shown in Figure 6.

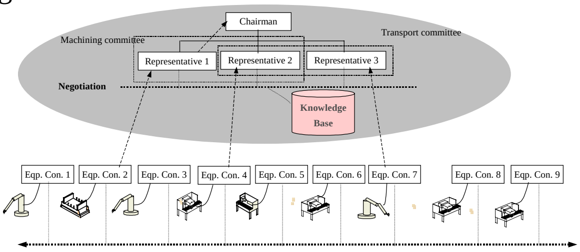

Figure 6. Structuring the legislation

6 Structure of the Judicature

The judicature makes a judicial decision upon the suit submitted by the administration and the equipment controllers based on the decision rules established by the legislation, and may request the legislation to establish new decision rules or change the current decision rules. The top level of the judicature is called the "*Chief justice*", under which there are some numbers of justices. Similar to the chairman in the legislation, the chief justice coordinates the activities among judges. The judges cooperate with each other through negotiation. Several judges can constitute a court, according to the submitted as shown in Figure 7. In order to construct an initial judicature structure, the judges with an average control-characteristic parameter are selected from the equipment controllers. An exemplary judicature construction is shown in Figure 7.

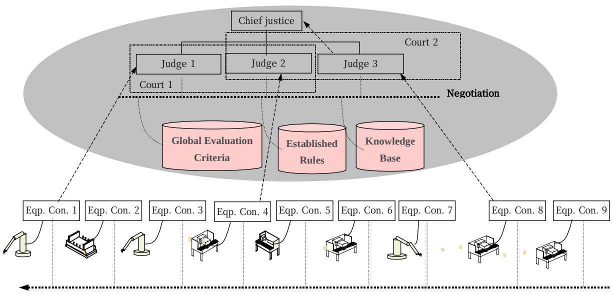

Figure 7. Structuring the judicature

7 Case-based Control Scenarios

Under the normally operating situation, the shop is operated only by the administration and equipment controllers. For an exemplary process plan and a shop (Figure 8), the interactions either between the administration and equipment controllers, or the negotiations among equipment controllers are shown in Figure 9.

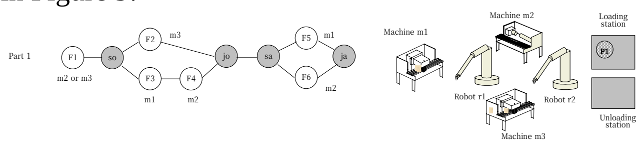

Figure 8. Exemplary part with a process plan and a shop floor layout

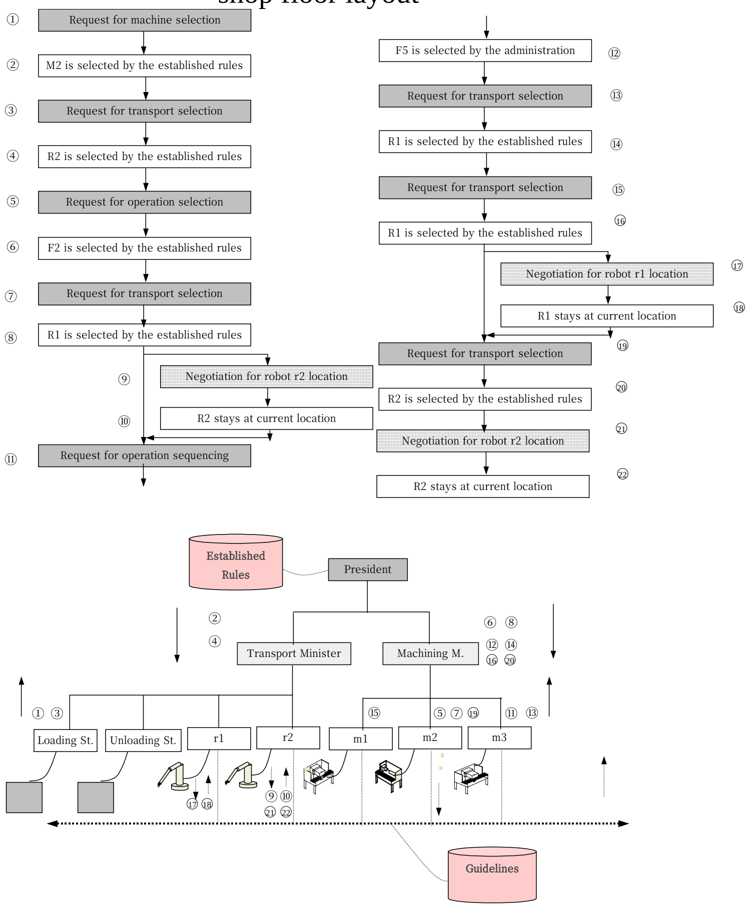

Figure 9. Exemplary normal process

Various conflicts between the equipment controllers and the administration are resolved by the judicature. For example, an equipment controller may ignore global optimization in making decisions. In particular, deadlock should be detected and resolved from the global point of view. To avoid a deadlock situation, the administration proposes a deadlock-free schedule to the equipment controllers. If the equipment controllers reject the provided schedule, the administration brings a suit that is resolved by the judicature as shown in Figure 11.

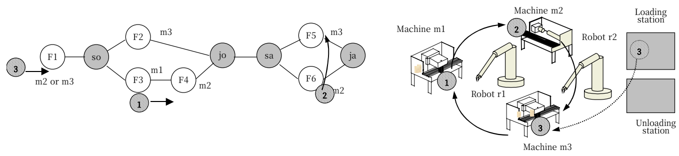

Figure 10. Part flow deadlock

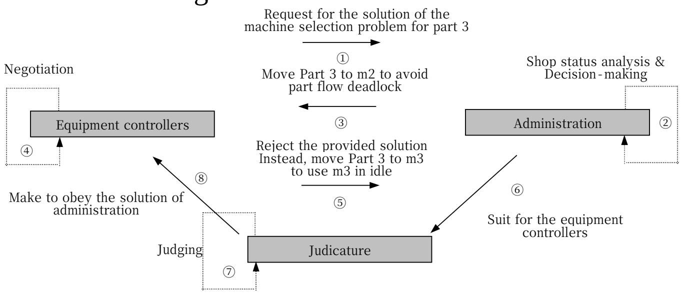

Figure 11. Interactions among equipment controllers, administration, and judicature

8 Conclusion

A lot of control architectures have been proposed for the SFC. Among the proposed architectures, heterarchical, hierarchical, and hybrid control architectures are popular due to their useful properties. Nevertheless, they have defects which can be overcome by the proposed DCA as shown in Table 2. They have common defects such as hard to reflect the changing demands of parts with process plans adaptively and no evaluation of the performance of controllers.

Table 2. Defects of the previous control architectures vs. solutions of the DCA

Architecture	Defects	DCA
Common	Hard to reflect the changing demands of parts with process plans adaptively	Adaptation to the changing demands of parts
Common	No evaluation of the performance of controllers	Definite evaluation procedure
Heterarchical	Too frequent traffic for communication	Relatively small communication
Heterarchical	Slow response due to communication and bidding	Relatively fast response
Heterarchical	Vague control mechanism	Definite mechanism
Heterarchical	Hard to achieve global optimum	Guarantee global optimum
Heterarchical	Hard to resolve conflicts among controllers	Definite procedure for conflict resolution
Heterarchical	Vague responsibility when problems occur in control	Responsibility examination by the legislation
Hierarchical/ Hybrid	Centralized control power	Respective independence of the three powers
Hierarchical/ Hybrid	Hard to adaptively cope with the disturbances	Adaptation to the disturbance
Hierarchical/ Hybrid	Hard to adaptively cope with the changing environment	Adaptation to the changing environment
Hierarchical/ Hybrid	Based on rigid master/slave architecture	Flexible architecture

The paper suggests the new paradigm of the control architecture, namely the democratic control architecture. It provides the mechanism of respective independence of the three powers and identifies the procedure of evaluation of controllers. High-performance and adaptability can be simultaneously achieved with the support of proposed framework. Hence, the SFCS will be rapidly adaptive to the changing manufacturing environment to cope with the ceaseless fluctuations in the supply chain.

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