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Guidelines for Evaluating the Ease of Reconfiguration of Manufacturing Systems

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Abstract- **This paper presents guidelines for evaluating the ease of reconfiguration of manufacturing systems. Based reconfigurability measurement tools proposed in the past [1], [2] and a reconfiguration process model, the paper proposes a method that can be used to assess different system characteristics. After the guideline is presented, an example of how the method can be applied to a batch processing system is given. It is found that the proposed method can be applied to batch processing systems based on ISA S88 batch server commercial software.**

I. Introduction

Manufacturing practices in the future will have to cope with customers demanding low cost products whose needs are likely to change quickly. Hence, manufacturing operations will have to be organized differently and be more effective in responding. Traditional centralized manufacturing planning, scheduling and control mechanisms have been found incapable of supporting changing production methods of highly dynamic variations in product requirements [3]. Because of this, much research effort [3],[4] is being devoted to develop manufacturing systems which are able react to changes rapidly and cost-effectively. To satisfy the need to react to change quickly according to the market, reconfigurable manufacturing systems are proposed as a possible solution [5]. Although, many technologies, such as modular machine tools [6], distributed automation [7], and multi-agent systems [8], have been developed to enable reconfigurability in manufacturing systems, little effort has been devoted to measuring the underlying reconfigurability of the proposed manufacturing systems [2],[1]. Thus, it is not known whether the developed systems achieve their intended level of reconfigurability. Moreover, it is not possible to compare the effort required to reconfigure a manufacturing system when two different methods or architectures are used

In order to evaluate the effort required to reconfigure a manufacturing system, measurement tools and associated usage guidelines should be defined. This paper focuses on the latter issue, providing a guideline for combining and using the available reconfigurability measurement tools [2], [1]. The aim of the evaluation guideline is to evaluate the effort required to configure (create a manufacturing system from scratch) or reconfigure a manufacturing system when the initial configuration and desired configuration of the manufacturing system have already been defined. Such an evaluation can be used to select the integration method or system architecture which typically requires the least reconfiguration or configuration effort.

II. Background

This section gives an introduction to reconfigurability as a property in a manufacturing system. The previous work relating to reconfigurability measurement is also reviewed. Finally the gaps between reconfigurability measurement requirements and existing tools are identified.

A. *Manufacturing reconfigurability*

Many definitions of reconfigurability have been proposed throughout the literatures. The two indicative definitions are "the ability to repeatedly change and rearrange the components of a system in a cost-effective way" [9] and "the ability of a function of a manufacturing unit to be simply altered in a timely and cost effective manner" [10]. The first definition only focuses on rearranging the components of a manufacturing system while altering the functions of the manufacturing system is not explicitly considered. On the other hand the second definition only focuses on modifying the functions of a manufacturing system without considering the rearrangement of the components in the manufacturing system. Moreover, both definitions do not explicitly mention that not all reconfigurations are desirable [1]. To address these issues Farid [1] has defined the term reconfigurability as "the ability to add, remove and/or rearrange in a timely and cost-effective manner the components and functions of a system which can result in a desired set of alternate configurations". The definition suggests that a manufacturing system with high reconfigurability should require less time an effort in order to reconfigure the system. This definition will be used in this paper.

B. *Tools for measuring reconfigurability*

Although comparatively little effort has been devoted to evaluate the reconfigurability of a manufacturing system, modularity, as a sub-characteristic of reconfigurability [4], has received much attention in fields as various as product design, manufacturing and software engineering [11]. It has been found that modular product have an enormous impact on the cost and speed of the development and the production of customized and multi-generation products [12]. It is also been discussed, in the software engineering domain, that modularity improves changeability of the software [13]. In order to

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achieve a high level of modularity, the interactions (or coupling) between modules within a product (or software) should be minimized [12]. Based on the modularity literatures and axiomatic design theory [14], it is proposed that the combination of Design Structure Matrix (DSM) and manufacturing Degree Of Freedom (DOF) can be used to evaluate the reconfigurability of automated manufacturing systems [1]. DSM is used to capture the interactions between manufacturing elements in the production system. The physical capabilities of the physical machines are captured by DOF. The results from DOF and DSM are then combined to calculate reconfigurability of manufacturing systems.

However, it is assumed that all the machines and software components were setup beforehand and there was no need to modify the internal control program of a machine when a manufacturing system is to be reconfigured [1]. The only things needed in order to reconfigure a manufacturing system are to "de-couple" or "re-couple" the interfaces between the modules in the manufacturing system. This might not be the case, since the control programs of the machines may need to be modified when reconfiguring a manufacturing system. Chirn and McFarlane [2] evaluated the effort required to reprogram or create the cell control software by calculating strategic complexity of the control system software, operational complexity of the control system software, extension rate, and reuse rate. This method mainly focuses on evaluating the complexity of the control programs of the controllers, but does not focus on interfaces or capabilities of the manufacturing systems. The combination of complexity, DSM and DOF should lead to more comprehensive tools for evaluating manufacturing system reconfigurability. Structural complexity of the software also can be evaluated using cyclomatic complexity [15].

III. THE PROBLEM: MEASURING "EASE OF RECONFIGURATION"

In order to measure the ease of reconfiguration of manufacturing systems, first it must be clarified what the ease of reconfiguration of manufacturing systems is. This section presents the model of a manufacturing system reconfiguration process. Then based on the model, the ease of the reconfiguration process is defined.

A. *Reconfiguration process model*

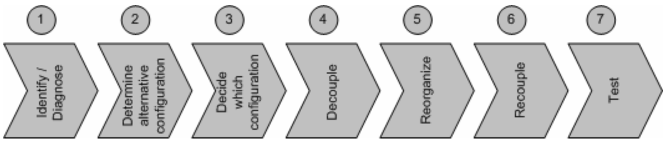

Fig. 1. Reconfiguration process model [16]

According to Fig. 1 is the reconfiguration process is comprised of 7 steps; identify/diagnose, determine alternative configuration, decide which configuration, de-couple, reorganize, re-couple, and test. Each step is described below. Note that the reconfiguration process may need to be done iteratively.

Step 1. Identify / Diagnose: The requirements for reconfiguring the manufacturing system are defined in this step. The requirements are based on the expected characteristics of the manufacturing system. Some examples of the requirements are throughput and types of products to be manufactured, after the manufacturing system has been reconfigured.

Step 2. Determine alternative configurations: All the configurations of the manufacturing system that will satisfy the requirements defined in Step 1 are listed in this step.

Step 3. Decide which configuration: Based on the configurations defined in Step 2 and the selection criteria, the best configuration is chosen. The selection criteria may include, cost, time, effort required to reconfigure the system, etc. The process of obtaining all the required software and hardware is also considered as part of this step.

Step 4. Decouple: Some modules in the initial configuration of the manufacturing system must be de-coupled or pulled a part. The decoupling is required if the existing modules are to be removed from the original manufacturing system or moved to other part of the system. Note that the modules include physical modules such as machines and logical modules such as software components.

Step 5. Reorganize: The decoupled modules and the new modules to be added are moved or rearranged so that they are in the new configurations where they will be ready to be recoupled to create the desired manufacturing system. Some modules may need to be setup so that it can be recoupled to the other modules in the manufacturing system. The setup process may include, programming, configuring internal parameters (excluding interface related parameters which will be configured in step 6) of the modules, etc.

Step 6. Recouple: All the decoupled or newly added modules are connected to the other modules in the manufacturing system to create the new manufacturing system that meets the requirements.

Step 7. Test: The newly reconfigured manufacturing system is tested and commissioned in this step to make sure that it meets all the requirements and operates reliably.

B. *Reconfiguration potential and reconfiguration ease*

Instead of describing a reconfiguration process as shown in Fig. 1, Farid [1] suggested that the reconfiguration process is comprised of the process of deciding what are the required manufacturing capabilities and the process of connecting the capabilities together to create a manufacturing system. A manufacturing is considered to have high reconfiguration potential when it has a large number of manufacturing capabilities [1]. Reconfiguration ease is the effort required to disconnect and/or connect the modules once the initial configuration and the final configuration of the manufacturing are known [1]. Based on this definition and the reconfiguration process model shown in Fig. 1, the problem of measuring the ease of reconfiguration includes evaluating the effort required to perform reconfiguration Step 4 to Step 7 as shown in Fig. 2

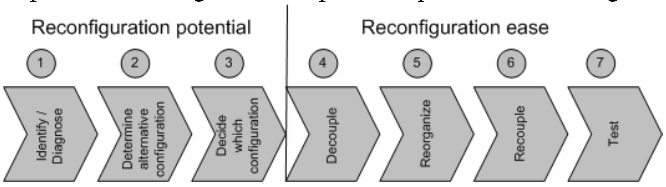

Fig. 2. The reconfiguration steps associated with reconfiguration ease and reconfiguration potential

In summary the scope of the ease of reconfiguration measurement can be defined as follows. The ease of reconfiguration measurement focuses on the effort required to perform the reconfiguration process of a manufacturing system when the initial configuration and desired configuration of the manufacturing system have already been defined. The reconfiguration steps included in the measurement process are decouple (Step 4), reorganize (Step 5), recouple (Step 6) and test (Step 7)

IV. TOOLS FOR MEASURING THE EASE OF RECONFIGURATION

This section describes which tools can be used to evaluate the ease of reconfiguration. The measurement is done by evaluating the effort required to perform the reconfiguration steps associated with reconfiguration ease (reconfiguration step 4 to step 7) as shown in Fig. 2. The tools to be used are the so called DSM [17] and software complexity [2]. The matching between the measurement tool and reconfiguration step in Fig. 1 is discussed below.

The first reconfiguration step to be considered is step 4 (decouple). In this step, some modules are disconnected from the system so that they can be removed or moved to other part of the system. In order to disconnect a module, the interfaces between the module to be disconnected and the manufacturing system must be decoupled. Since this task mainly relates to the interfaces, the DSM which is used to capture all the interfaces between modules in the system can be used to capture the effort required to perform decoupling. However, in this case only the interfaces to be removed are considered. Reconfiguration step 6 (recouple) also relates to the interfaces between modules in the manufacturing system. Since, in this step, the interfaces between the disconnected or the newly added modules and the other modules in the system are to be created. Thus, the DSM can also be used to capture the effort required to perform recoupling. However, only the interfaces to be created or connected are considered. The number of interfaces can be used to reflect the required effort in reconfiguration step 4 and 6. The greater the number of the associated interfaces is, the greater the required effort for creating or removing the interfaces [1]

The preparation of the modules to be added or connected is done in reconfiguration step 5 (reorganize). The tasks in this step involve creating (or modifying) the control software and configuring the internal parameters of the modules. Strategic complexity which is used to capture the size of the control program can be used to evaluate the effort required to create or modify the program. The required effort is calculated by finding the difference between the strategic complexity of the final configuration and initial configuration of the manufacturing system. Again the larger the value of strategic complexity is, the more the required effort to create or modify the control program. Cyclomatic complexity [15] which is used to represent the complexity of task structure is used to capture the effort required to create or modify the control program. The higher the value of cyclomatic complexity, the more the effort required in order to understand and create or modify the program [15].

The effort required to perform testing in reconfiguration step 7 is directly proportional to the effort required in Step 4, 5, and 6. If the number of the modified interfaces is large and the complexity of the created program is high, the effort required to integrate and test the whole system should be also high. Thus, it is not necessary to explicitly calculate the effort required in Step 7. It can be assumed that the effort required in Step 7 is implicitly included in the evaluation results of Step 4, 5, and 6.

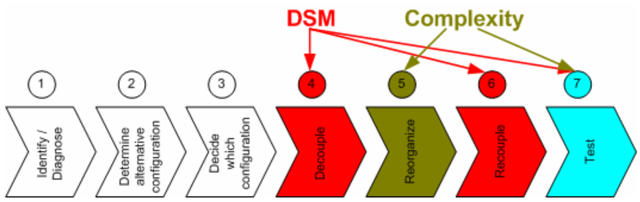

Fig. 3 The evaluation tools and reconfiguration steps

Fig. 3 shows the mapping between the reconfiguration steps and the tools used to evaluate the required effort in order to perform each reconfiguration step. DSM is used to evaluate the effort required in Step 4 decouple and Step 6 recouple. The effort required in Step 5 can be evaluated by calculating the complexity. The effort required to perform Step 7 test is not calculated explicitly, since it assumed to be directly proportional to the resultants DSM and complexity.

V. GUIDELINES FOR ASSESSING EASE OF RECONFIGURATION

This section describes how the tools can be used to evaluate the ease of reconfiguration of a reconfiguration process of a manufacturing system. It begins by describing the overall guidelines. Then the guidelines of how to use DSM and Complexity to evaluate each reconfiguration step are presented.

A. *Guideline overview*

The guidelines for assessing the ease of reconfiguration of the whole reconfiguration process are summarized below.

1. Define the initial configuration and final configuration of the manufacturing system to be reconfigured.

2. Evaluate the effort required to perform decoupling (reconfiguration step 4) by creating the associated DSMs. Then Based on the information about all the interfaces captured in the DSMs, the total number of interfaces to be recoupled are calculated.
3. Evaluate the effort required to perform reorganizing (reconfiguration Step 5) by calculating the total complexity of the reconfiguration process. This is done by creating Petri net models for the manually created programs. The total complexity of the reconfiguration process is calculated from the Petri net models.
4. Evaluate the effort required to perform recoupling (reconfiguration step 6) by creating the associated DSMs. Then Based on the information about all the interfaces captured in DSMs, the total number of interfaces to be decoupled are calculated.
5. Repeat step 2 to 4 for each of the interested reconfiguration method.
6. The results of the different reconfiguration methods are compared.

B. *Using DSM to evaluate the effort required to add, remove or modify the interfaces*

DSM is used to evaluate the effort required to decouple (reconfiguration step 4) and recouple (reconfiguration step 6) the manufacturing elements. Since, it captures all the interactions between the manufacturing components. A total of six DSMs are created to capture different types of interactions between manufacturing modules. The first three DSMs so called "conventional DSM" are used to capture the messages sent between conventional modules which are software components and physical equipments. The messages sent between the modules are classified into three types; Interface TypeI, Interface TypeII, and Interface TypeIII, based on how the interfaces are created. The TypeI interfaces are the interfaces in which their infrastructures are provided in advance. To create this type of interface, the system integrator only has to setup the parameters of the interface. Type II interfaces are the interfaces where the interfaces on one side of the communication links are provided in advance. The interface programs on the other side of the communication links must be manually created by the system integrator. In the case of TypeIII interfaces, interfaces on both sides have to be manually created. A conventional DSM is used to capture one type of interface. Thus three conventional DSMs are required. The other three DSMs so called "functions based DSM" are used to capture the message sent between functional modules. A functional module encapsulates all the functions required by a machine in order to work properly. The following rules are used to compare the effort required to recouple or decouple the manufacturing elements.

Rule 1: A TypeIII interface requires most effort and a TypeI interface requires least effort in order to be recoupled or decoupled.
Rule 2: The larger the number of interfaces is, the more the effort required to recouple or decouple.

C. *Using complexity to evaluate the effort required to create, remove or modify the control program*

Complexity is used to capture the effort required to modify the control software which resides within a conventional module. However, the control software to be created or modified can be in various forms such as ladder logic program, sequential flow chart or Petri net. Thus, to generalize the use of the complexity evaluation method, the method should be able to be used to evaluate all form of control software. To solve this issue, it is proposed that the control software should be converted into the same form. In this paper, Petri net model is used. Based on the created models, strategic complexity (SC) [2] and cyclomatic complexity (CC)[15] can be calculated using (1) and (2).

$$SC = P + A + T \tag{1}$$

Where:

P is the total number of manually created or modified places of all Petri net models for a reconfiguration method

A is the total number of manually created or modified arcs of all Petri net models for a reconfiguration method

T is the total number of manually created or modified transitions of all Petri net models for a reconfiguration method

$$CC = A - (P + T) + N \tag{2}$$

Where:

N is the total number of Petri net models for a reconfiguration method

D. *Comparing the ease of reconfiguration*

To compare the ease of reconfiguration of different reconfiguration approaches, the total number of interfaces to be modified and complexity of the different approaches are compared. To conclude that reconfiguration approach "A" requires less effort then other approaches, all the following conditions must be met.

1. The number of interfaces to be modified in reconfiguration Step 4 of "A" is less than other methods.
2. The complexity of "A" is less than other methods
3. The number of interfaces to be modified in reconfiguration Step 6 of "A" is less than other methods.

VI. EVALUATING THE MANUFACTURING SYSTEM EASE OF RECONFIGURATION: AN EXAMPLE

This section presents an example of how the proposed guideline can be used. It is intended that the proposed guideline will be used to evaluate the effort required to reconfigure an automated discrete manufacturing, since both complexity [2] and DSM [1] were originally used to evaluate the reconfigurability of an automated discrete manufacturing system. However, the method should also be able to be applied to other classes of manufacturing system. To demonstrate that it is feasible to apply the method to other class of the manufacturing system, an example of how the method can be used to evaluate the effort required to configure or setup a batch manufacturing system is discussed in this section. The layout of the manufacturing system and its control architecture are shown in Fig. 4. The architecture of the manufacturing system is based on the ISA S88 standard [18]. The example manufacturing system is modified from an example system discussed in InBatch software manual [19].

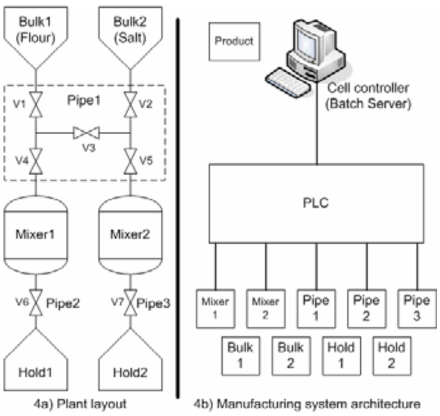

Fig. 4 The manufacturing system layout and its control architecture

The manufacturing system is used to produce chicken spice. The initial condition of the manufacturing system before starting the production process are; all equipments are clean, there is flour in bulk1, salt in bulk2, and chicken in either mixer1 or mixer2. The production recipe for the chicken spice is shown Fig. 5.

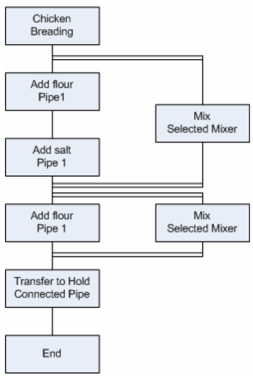

Fig. 5 The production recipe

The ease of reconfiguration of the example can be evaluated using the guideline described in Section V as presented below.

Step 1 Define the initial and final configuration of the manufacturing system: In this case the manufacturing system is created from a green field site. Thus, there is no manufacturing system in the initial configuration. The desired configuration of the manufacturing system is the formation completed manufacturing system shown in Fig. 4.

Step 2 Evaluate the effort required to perform decoupling (reconfiguration step 4): Since the manufacturing system is built from scratch, there is no interface to be decoupled.

Step 3 Evaluate the effort required to perform reorganizing (reconfiguration step 5) by calculating the total complexity of the reconfiguration process: This can be done by following the guidelines for calculating complexity discussed in Section V-C. First all the required control programs have to be identified. Then it is investigated whether each program has to be manually created or modified. The required control programs are shown below in Table 1.

Program / software	manually created
Batch Server (InBatch)	No
Equipment Model setup in the Server	Yes
Production recipe	Yes
PLC program for Mixer1	Yes
PLC program for Mixer2	Yes
PLC program for Pipe1	Yes
PLC program for Pipe2	Yes
PLC program for Pipe3	Yes

Table 1 List of the required control software

To simplify the example, only the Petri net model and the complexity for the production recipe will be calculated. Based on the production recipe shown in Fig. 5 the Petri net model can be created as shown in Fig. 6. Then by using (1) and (2) the complexity of the model is calculated. In this case SC is 27 and its CC is 2.

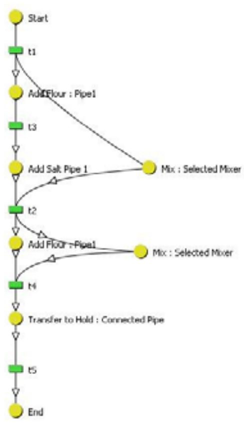

Fig. 6 Petri net for production recipe

Step 4 Evaluate the effort required to perform recoupling (reconfiguration step 6): This can be done by following the DSM guidelines described in Section V-B. To do this first the modules have to be identified. For this example the conventional modules are; product, batch server, PLC, Mixer1, Mixer2, Hold1, Hold2, Bulk1, Bulk2, Pipe1, Pipe2, and Pipe3. The function based modules for the example are Mixer1, Mixer2, Pipe1, Pipe2, Pipe3, Bulk1, Bulk2, Hold1, Hold2, and

Product. Then the interfaces between the modules are captured. Next the DSMs are created. An example of conventional DSM capturing Interface TypeI is shown below in Fig. 7.

	Batch Server	Mixer1	Mixer2	PLC	Pipe1	Pipe2	Pipe3
Batch Server		0	0	0	0	0	0
Mixer1	0		0	3	0	0	0
Mixer2	0	0		3	0	0	0
PLC	0	2	2		5	1	1
Pipe1	0	0	0	14		0	0
Pipe2	0	0	0	4	0		0
Pipe3	0	0	0	4	0	0	

Fig. 7 Conventional DSM capturing Interface Type I messages

Based on the created DSMs total number of Interface can be calculated. For this example, There are 68 TypeI Interfaces, 42 TypeII Interfaces, and 39 TypeIII Interfaces.

Step 5: Repeat step 2 to 4 for all other approaches: Since there is no other approaches there is no need to perform this step.

Step 6: Compare the results of the different approaches: The comparison guidelines described in Section V-D can be used for this purpose. However, since there is no other approach to be compared, this step cannot be performed.

VII. SUMMARY

The guidelines for evaluating reconfiguration ease have been described in this paper. The guidelines can be used to compare the different reconfiguration methods. It can also be used to assist the design process by identifying all the required interfaces and control programs. It is shown in the example that the guidelines can be applied to evaluate batch processing plant. It is expected that the results will be used to compare one reconfiguration method with other methods. Thus the results of a single reconfiguration approach in the case of the example are not very useful. Though the results suggest that to setup the manufacturing system 68 TypeI Interfaces, 42 TypeII Interfaces, 39 TypeIII Interfaces and 7 control programs have to be created or modify.

There are some difficulties when applying the guidelines to the example. The difficulties are listed below.

1. It is not trivial to create Petri net models in which their places represent the same granularity of task which required the same amount of effort in order to created or modify.
2. It may not be possible to identify all interfaces especially the interfaces between function based modules. Since some of the interfaces are embedded within commercial software.
3. It is not trivial to decompose the messages so that the decomposed messages required the same amount of effort to create or modify the interfaces used to deal with the messages.

Issue 1 and 3 can be partially solved by applying the same rules for identifying places for Petri net models and decomposing the messages for all reconfiguration approaches. It is expected that the proposed guidelines will be applied to other reconfiguration approaches implemented in the University of Cambridge Automation Laboratory.

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