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A TOOL FOR ASSESSING RECONFIGURABILITY OF DISTRIBUTED MANUFACTURING SYSTEMS

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Abstract: In recent years, a large number of approaches to developing distributed manufacturing systems has been proposed. One of the principles reasons for these development has been to enhance the reconfigurability of a manufacturing operation; allowing it to readily adapt to changes over time. However, to date, there has only been a limited assessment of the resulting reconfigurability properties and hence it remains inconclusive as to whether a distributed manufacturing system design approach does in fact improve reconfigurability. This paper represents part of a study which investigates this issue. It proposes an assessment tool – the so called ”Design Structure Matrix” as a means of assessing the modularity of elements in a manufacturing system. (Modularity has been shown to be a key characteristic of a reconfigurable manufacturing system.) The use of the Design Structure Matrix is illustrated in assessing a robot assembly cell designed based on distributed manufacturing system principles.

Keywords: Reconfigurable Manufacturing Systems, Reconfigurability, Modularity, Design Structure Matrix

1. INTRODUCTION

Recent trends in manufacturing are characterized by continually evolving and increasingly competitive marketplaces. The effective implementation of lean manufacturing principles, in many instances, had freed excess capacity, and thus gave consumers greater influence over the quality, quantity and variety of products(**?**)(**?**). In order to stay competitive, manufacturing firms have had to respond with high variety products of increasingly short product life cycle (**?**). In other words, the products must be introduced to the market in ever short time and increasing frequency so as to continually develop the variety of the offered product range.

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1.1 Reconfigurable Manufacturing Systems Requirements for Achieving Competitiveness

Mass-customized and short life cycle products drive many requirements on both the behavior and the structure of a manufacturing system. With respect to system behavior, the planning, scheduling, and execution control algorithms must respond effectively to changing conditions of orders, stock-levels, and manufacturing resources (**?**). In a mass-customized environment, the existence, contents, priority and deadline of a given order may change over the course of the manufacturing operation. This may in turn require greater responsiveness to stock-outs of raw material and work-in-progress. Finally, this responsiveness must further consider machine availability in terms of its capacity and breakdown frequency.

The structure (or architecture) of a manufacturing system should also be considered in a mass-customization, short product life cycle environment. The continual introduction of new product families and their associated variants requires that capacity be adjusted flexibly with the addition of new production and material handling resources and/or their tooling. Similarly, new product introduction may require that the manufacturing system be rapidly redesigned in terms of a rearrangement of its component production and material handling resources (?). Each of these reconfigurations require extensive integration effort. At a low level, the mechanical interfaces between production resources, products and material handlers must be addressed. In addition, at a high level, each new production resources and material handler with their associated tools, fixtures and end-effectors require integration into the continuous-real-time, discrete event, scheduling, and planning control layers (?).

Assessing the suitability of a manufacturing system to these drivers requires measure of both its operation (behavioral) performances and its system (structural) performance. Measure for the former are well developed in the literate and industry. Among them are throughput, overall equipment effectiveness, etc. Measures of the structural performance, however, have been more elusive. As a result, assessing the reconfigurability of manufacturing systems based upon its structural properties has been difficult (?).

1.2 Manufacturing System Scope

This paper restricts its scope to distributed manufacturing systems (DMS). A distributed manufacturing system is a system that transforms raw material into finish product via a collection value-adding and material handling resources which are controlled by a DMS control system. A DMS control system is a system that controls the planning, scheduling, execution and continuous-time control functionality with decision elements distributed among the DMS's value-adding and material handling resources. A conceptual representation of a distributed manufacturing system is shown in Figure 1.

1.3 Paper Outline

Having defined the scope of a manufacturing system and motivated the need for the assessment of reconfigurability, this paper in Section 2 will review the techniques that have been used to evaluate the reconfigurability of distributed manufacturing systems. Section 3 will describe why reconfigurability evaluation is difficult and identify

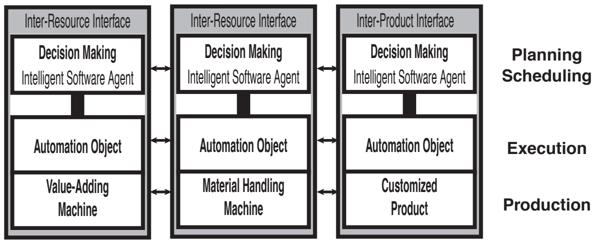

Fig. 1. A Conceptual Representation of a Distributed Manufacturing System

the key characterizes by which it should measured. Section 4 will focus on the first of these characteristics – modularity, and propose the "Design Structure Matrix" as a tool by which it can be measured. The section will also seek to motivate the tool with a simplified motivating example of an existing distributed manufacturing system. Finally, Section 5 will summarize the value of the design structure matrix and discuss future work necessary for a holistic approach to measuring reconfigurability.

2. EVALUATION TECHNIQUES RELATED TO RECONFIGURABILITY IN DISTRIBUTED MANUFACTURING SYSTEMS: A REVIEW

In relation to the scope previously defined a number of distributed manufacturing system architectures have been proposed. Of these, three, PROSA, ADACOR and HCBA have been designed as reference architectures and later implemented into specific cases as system architectures (?)(?)(?)(?). PROSA's evaluation method was primarily qualitative. Evaluation techniques from the architectures of buildings and object-oriented software were borrowed in order to discuss descriptively the adherence of the architecture to the identified design requirements (?). The evaluation method also relied on the flexibility of the architecture's associated algorithms (?). ADACOR's evaluation technique measured operational performance metrics such as throughput and lead time under various disturbance scenarios as a function of varying architectures: hierarchical, heterarchical and hybrid (ADACOR) (?). Here, the comparison could be made due to the adaptive nature of the ADACOR architecture because it used an algorithm similar to the baseline hierarchical and heterarchical architectures. HCBA used structural metrics such as petri-net complexity and lines of code. These metrics were then used to calculate extension and reuse rates for various reconfigurations such as the addition of a new machine (?).

These evaluation techniques suggest a lack of effective methods to assess the reconfigurability of a DMS architecture's performance. In the case of the first two architectures discussed, evaluation was carried out qualitatively or quantitatively by measuring operation (behavioral) performance. The last of the architectures, HCBA, added to the evaluation literature by proposing structural metrics. However, the relationship of these metrics to reconfigurability needs to be clarified in order to make conclusive statements about reconfigurability improvements.

3. ASSESSMENT OF RECONFIGURABILITY IN DISTRIBUTED MANUFACTURING SYSTEMS

Assessment of the reconfigurability of a distributed manufacturing system structure or architecture is difficult. Three things are required: 1.)identification of structure dependent measurables/characteristics that determine reconfigurability, 2.) methods of quantitatively modelling the system structure and 3.) formulaic techniques of relating the former to the latter.

3.1 Key Characteristics of Reconfigurability

Intuitively, reconfigurability concerns the facility with which components of a system maybe 1.)pulled apart 2.)rearranged and 3.) reconnected. It also concerns the interfaces between these components. More formally, Mehrabi identifies an RMS as having the following five key characteristics (**?**):

- Modularity: The degree to which all system components, both software and hardware are modular.
- Integrability: The ability with which systems and components maybe readily integrated and future technology introduced.
- Convertibility: The ability of the system to quickly changeover between existing products and adapt to future products.
- Diagnosability: The ability to quickly identify the sources of quality and reliability problems that occur in large systems.
- Customization: The degree to which the capability and flexibility of the manufacturing system hardware and controls match the application (product family).

	Pull Apart	Reorganize	Put Together	Standard Interfaces
Modularity	X	X	X	X
Integrability		X	X	X
Convertibility		X		X
Diagnosability	X		X	
Customization		X		

Fig. 2. A Mapping of Reconfigurability Key Characteristics to Intuitive Features

Returning to the intuitive issues, the table in Figure 2 relates the key characteristics to their respective intuitive features. Modularity appears to affect all of the intuitive factors but the other characteristics play a significant role. Integrability and convertibility seem to have similar roles with respect to standardized interfaces and reorganization. While diagnosability seems to factor into the facility of pulling apart and putting together system components. Customization appears to only aid the reorganization of components. This analysis suggests that reconfigurability assessment needs to examine several different dimensions of a manufacturing system. The contribution in the next section proposes a tool – traditionally used in product design – to support the assessment of manufacturing system modularity.

4. MODULARITY ASSESSMENT USING THE DESIGN STRUCTURE MATRIX

This section proposes the design structure matrix (DSM) as a tool for assessing the modularity in reconfigurable manufacturing systems. First, the DSM is introduced with a brief description. Second, the various usages of the DSM is reviewed. Finally, the DSM's applicability to manufacturing systems is motivated a simplified example.

4.1 Description of Design Structure Matrix

The design structure matrix is a systems analysis tool that captures the interactions, interdependencies, and interfaces between components of a complex system in a compact and and clear representation (**?**). Given two components A and B, they may may interact in a parallel, serial or coupled fashion. These interactions may be spatial, structural, energy, material or information interfaces (**?**)(**?**). Figure 3 shows the graphical representation of these interactions and their associated design structure matrices. The placement

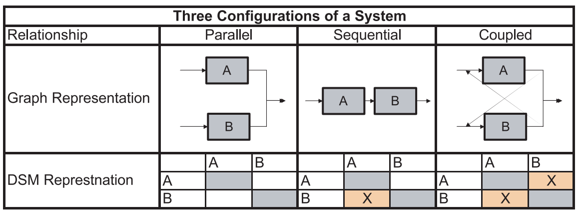

Fig. 3. DSM Tutorial

of an off-diagonal "X" represents the existence of an interaction between two components A and B (**?**). Some authors, however, have replaced the "X" with numerical values in order to subjectively assess the strength of a particular interaction (**?**)(**?**)(**?**). A tutorial of the DSM can be found at (**?**) and is formally described in (**?**).

4.2 Usage of the DSM: An Overview

The DSM has found many uses in the field of product design. Within the scope of this discussion, the most relevant of these is 1.) the modelling of the system structure 2.) calculating the modularity of that system. Pimmler and Eppinger used the DSM to model the structure of an automotive climate control system and then used the analysis to advance concepts in the modularity of subsystems (**?**). Similarly, Sosa et al. used the DSM to analyze the interactions of a large commercial aircraft engine. The analysis was used to advance a methodology to allocating design teams to major aircraft subsystems (**?**)(**?**). In this latter case, one can draw an analogy between the transportive and transforming functions of an aircraft engine to those of manufacturing systems. Both systems also require many layers of control and are similarly complex. Although a discussion of much smaller scope, Kusiak used a DSM to capture the coherence of information interfaces in SADT models of manufacturing control systems(**?**).

The DSM has also served as a data structure from which a variety of modularity metrics have been developed. Gershenson has conducted an exhaustive review of these metrics (**?**) and their associated definitions (**?**). Interestingly, there is much similarity between modularity applications in the field of product design and reconfigurability applications of distributed manufacturing systems. Huang and Kusiak have discussed matrix-based modularity metrics to facilitate the realization of highly customized products (**?**). The modularity in products necessary to achieve customization appears to correspond to modularity in distributed manufacturing systems to manufacture those products. Matrix-based modularity metrics have also been used to advance the role of modularity in life cycle engineering (**?**)(**?**)(**?**)(**?**). Analogously, modularity may play a role in the efficient operation, maintenance, and decommissioning of distributed manufacturing systems.

4.3 A Distributed Manufacturing System Example

A simplified DSM analysis can now be carried out to motivate the application of the tool to distributed manufacturing systems. The HCBA robotic work cell, shown in Figure 4, is taken for study. The system assembles a simple electrical meter box out of parts A,B, and C which are stored in an input and output buffer. The system is also composed of four manufacturing resources: a Hirata and Puma robot, a turn table and a flipper to which each has its associated execution code and resource agents. A complete discussion of the cell can be found in (**?**).

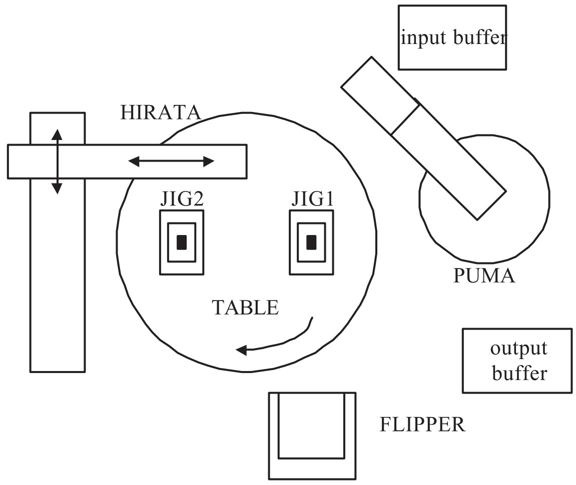

Fig. 4. A Schematic Diagram of the HCBA Robot Work Cell

Many steps are required to complete the analysis effectively and efficiently. First, the manufacturing system boundary has to well defined. Next, all major components of the system must be identified. These can be broadly categorized as value-adding and material handling resources, buffers, products and their associated tools, fixtures and control. Finally, the spatial, structural, material, energy and information flows between these components must be identified. Clearly, this analysis requires a great deal of detailed information – an observation previously made by the product design research community. However, it can be facilitated by using binary values in the matrix elements and recognizing design patterns which result in similar regions of interaction/non-interaction. The resulting DSM for the HCBA robotic work cell is found in Figure 5.

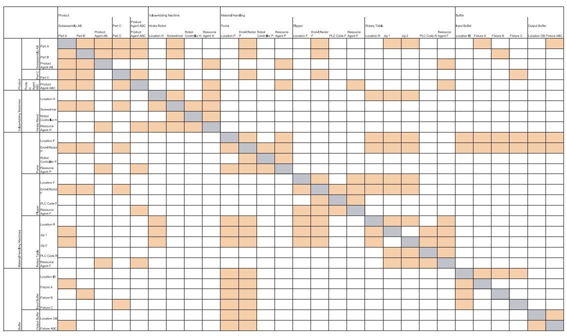

Fig. 5. A DSM of the HCBA robotic work cell

The HCBA robotic work cell design structure matrix immediately reveals the coupling among the system's components. The first observation is the central integrating role of the product. Not only must the product mechanical interface with all of the various tools, fixtures and end-effectors it encounters, but the product-agent acts as a coordinator of information communicated about the product to all of the value-adding and material handling machines. A second observation is the degree of heavy coupling along the block diagonal. This is to be expected as the block diagonals represent the tightly coupled intra-resource interactions. The integrative role of material-handling resources is also noted. In this particular system, the heavy role of the rotary table and the PUMA robot appears as clear coupling to the remainder of the system resources. Finally, the existence of white space in the DSM is as descriptive as marked elements. Here, the tertiary role of the buffers and the limited role of the Hirata robot becomes clear. This example demonstrates that the DSM description of a system gives an immediate graphical clarification of the where coupling exists. The designer is immediately directed towards regions of high coupling so that she may act to reduce coupling if at all possible while maintaining the system's functionality.

4.4 Advantages of the DSM

The previous sectioned demonstrated the potential of the design structure matrix as a tool for assessing the modularity of distributed manufacturing systems. The primary benefit of the tool is that it succinctly captures the structure of a system in terms of its structural, spatial, material, energy and information interfaces. Every coupling between any given two components can be potentially described. The matrix structure of design structure matrices also lends itself to quantitative modularity measurement through the use of off-diagonal summations.

5. CONCLUSIONS & FUTURE WORK

This paper has proposed a promising tool with which to analyze and compare the structure of distributed manufacturing systems. It has been shown to be particularly promising with respect to measuring modularity, one of the five identified key characteristics of reconfigurable manufacturing systems. Nevertheless, much work remains to utilize it effectively. Some investigation is still required to determine which of the previously mentioned modularity metrics is most suitable in the context of distributed manufacturing systems. Also, the size of a DSM grows quickly with the number of components. A systematic method for characterizing the types of interactions in a distributed manufacturing system would facilitate the potentially tedious work of identifying interactions between all of the various DMS components.

Despite its promise as a modularity tool, the DSM remains to be seen as an effective tool for assessing the integrability, convertibility, diagnosability, and customization characteristics of the DMS. These characteristics, however, are less understood from a quantitative perspective. As stated in Section 3, further methods for quantitatively modelling the distributed manufacturing system structure will be required. Once this has been done, formulaic techniques for relating these models to the four remaining RMS key characteristics will have to be developed.

There may exist other previously developed tools that can address the other reconfigurability key characteristics. Such tools would have to consider the value-adding and material handling processes in the system, previously undescribed by the design structure matrix. Similarly, new tools would have to compare the breadth of product families to the breadth of reconfigurations or rearrangements that the DMS is capable of undergoing. Finally, new tools should rigorously treat the system's observable state so as to address the diagnosability concerns of reconfigurability. The search and development of these tools will lead to all five key characteristics being. In this way, a holistic approach to assessing reconfigurability can be developed. (Abdi and Labib, 2003)(Abourizk and Sawhney, 1993)(**?**)

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