Measuring the Effort of a Reconfiguration Process

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***Abstract*—In recent years, the fields of reconfigurable manufacturing systems [1], holonic manufacturing systems [2], multi-agent systems [3] have made technological advances to support the ready reconfiguration of automated manufacturing systems. To help assess these advancements, a reconfigurability measurement process [4] has been developed based upon the complementary ideas of reconfiguration potential [4]–[6] and ease [4], [7]. This work measured the reconfigurability of an automated manufacturing system as an intrinsic property of the system's structure. However, it did not explicitly measure the effort required to realize a reconfiguration process. This paper recombines the concepts of reconfiguration potential and reconfiguration ease to measure the effort required to realize a specific class of reconfiguration processes. The theoretical developments are then demonstrated in an illustrative example. The paper concludes with a discussion of potential implications on adjacent research.**

I. Introduction

Recent trends in the global marketplace have necessitated the production of mass-customized products of increasingly short product life cycle [8]. These dual requirements have necessitated that enterprises find ways to quickly and incrementally adjust production capacity and capability. In other words, as the continually growing variety of products are introduced, ramped up, phased out, and finally made obsolete, the capabilities of production resources must be reallocated to the product variants that need them most. To fulfill these needs, the concept of reconfigurable manufacturing systems has been proposed as a set of possible solutions [1].

Definition 1.1: Reconfigurable Manufacturing System: [A System] designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements [1].

Over the years, many technologies and design approaches have been developed to enable reconfigurability in manufacturing systems. These have included modular machine tools [9], [10], distributed automation [3], [11], multi-agent systems [12] and holonic manufacturing systems [2]. To help assess these advancements, initial efforts to evaluate these design approaches have been reported [13]–[16] while more recently an integrated reconfigurability measurement process has been developed [4]. This work measured the reconfigurability of an automated manufacturing system as an intrinsic property of the system's structure, but did not explicitly measure the effort required to realize a reconfiguration process.

This paper recombines the concepts of reconfiguration potential and ease to measure the effort required to realize a specific class of reconfiguration processes. A five part discussion is followed. Section II introduces the intuitive notions and the associated models of reconfiguration potential and ease. Next, Section III shows how these models may be used to develop a measure of reconfiguration process effort. Section IV, then illustrates the measure in an example. The potential implications of this measure is then discussed in Section V.

Prior to proceeding, this paper restricts its discussion to the shop-floor activities of automated manufacturing systems as defined in Levels 0-3 of ISA-S95 [17]. Furthermore, only distributed manufacturing systems are discussed explicitly as previous work has shown how centralized systems may be converted into their distributed analogues [4], [7]. Throughout, reconfigurability is defined as:

Definition 1.2: Reconfigurability [4], [18]: 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.

However, in the context of this paper, reconfiguration processes are limited to the addition, removal and/or rearrangement of production resources and/or their associated components. Changes to the product line are not considered here.

II. Background

A simplified conceptualization of a reconfiguration process is shown in Figure 1. Essentially, when a manufacturing

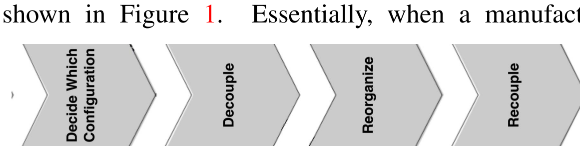

Fig. 1. A Four Step Reconfiguration Process

system is to be reconfigured, a new alternate configuration is first determined. Next, one or more resources may need to be decoupled from the rest of the system. These resources are then reorganized; perhaps to accommodate additional resources. Finally, all the resources including new ones are recoupled together. For example, the introduction of a milling machine into an automated production system might require material handling systems to be decoupled before being recoupled to the additional resource. From this description, a reconfiguration process can be viewed in terms of two complementary ideas: reconfiguration potential [4]–[6] and ease [4], [7]. The first of these addresses the first and third steps and depends primarily on the number of ways that the system's many components and functions may be decoupled, reorganized, or recoupled. The second of these is concerned with the effort required to realize those steps. This section discusses these two ideas intuitively and provides models for their description.

A. Reconfiguration Potential

Reconfiguration processes allow for step-wise changes in a system's capabilities so as to support the introduction, maturity, and obsolescence of product variants [1], [4]. Hence, to assess the potential for reconfiguration, it becomes important to understand how the system's capabilities are achieved by its various production resources. While some production resources are dedicated and can only realize one production process, others are more flexible and can realize many [1]. These processes include physical activities such as material removal or fixturing but they also include all of the necessary levels of control functions. For clarity, production resources and processes are defined respectively as:

Definition 2.1: Production Resource : a machine, material handler, or buffer $r \in R$ capable of realizing one or more production processes.

Definition 2.2: Production Process: a production resource-independent, manufacturing technology independent process $p \in P$ that either transforms raw material or work-in-progress to a more final form or transports raw material, work-in-progress, or final goods between a pair of machines or buffers.

Figure 2 gives a graphical representation of the capabilities of a simple production system consisting of two production resources outlined in solid lines. R_1 is a mill capable of a milling process P_1 and a drilling process P_2. R_2 is a lathe capable of a drilling process and a turning process P_3. As such a system undergoes reconfigurations, the number of resources can be changed or their components can be altered so that their associated capabilities are modified.

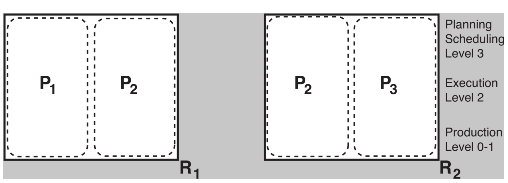

Fig. 2. Capabilities of Production Resources [4]

This intuitive conception of production capabilities has been mathematically modelled previously [4]–[6] using the design equation from the theory of Axiomatic Design for large flexible systems [19]. It relates the set of production resources R to the set of production processes P by a binary matrix J_S called a "knowledge base".

$$P = J_S \odot R \quad (1)$$

where the "matrix boolean multiplication" operator $\odot$ is defined as:

Definition 2.3: Matrix Boolean Multiplication $\odot$ [4], [6]: Given sets or boolean matrices B and C and boolean matrix A, $C = A \odot B$ is equivalent to:

$$C(i,k) = \bigvee_j A(i,j) \wedge B(j,k) \quad (2)$$

This production knowledge base J_S will be used extensively in the next section to measure the effort of a reconfiguration process.

B. Reconfiguration Ease

As stated in the beginning of the section, the ease of reconfiguration is concerned with the effort required to decouple, reorganize, and recouple resources. Hence, intuitively speaking, as an intrinsic property of the system, the complexity of the resources' interfaces affect the difficulty of the reconfiguration [4]. This intuitive concept has been confirmed repeatedly in the modularity literature [20], [21]. In product design, modular product architectures have a dramatic impact on the cost and speed of the development and production of customized and multi-generation products [22]. Meanwhile, in software engineering modularity has been shown to improve software's changeability [23].

Resource interfaces in manufacturing systems are particularly complex. The types of energy and information transferred can vary dramatically [4], [7]. Figure 3 shows some of the typical interfaces at the various levels of a production system. At the lowest level, the physical process occurs; often

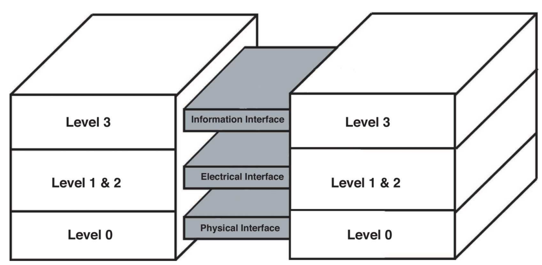

Fig. 3. Multi-Level Interfaces of Production Resources [4], [7]

along a mechanical, thermal or chemical interface. Higher up, the continuous real-time control layer typically has electrical interfaces such as time varying voltage signals. In Level 2, the discrete execution control interfaces are simultaneously electrical signals and binary information. Finally, at Level 3, the interfaces are entirely information. Information interfaces transfer of minimal amounts of energy but gain their importance by the meaning associated by the transfer.

This intuitive conception of production resource interfaces has been mathematically modelled previously [4], [7], [24], [25] using the design structure matrix [26]. As shown in Figure 4, it is a block matrix form where any two production resources

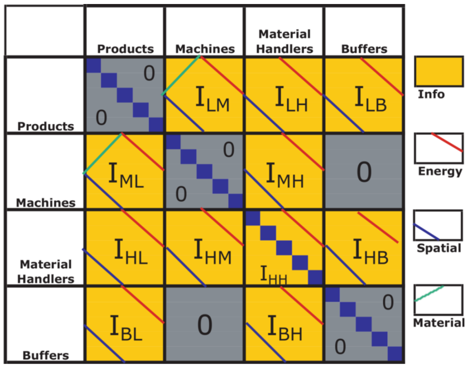

Fig. 4. Production Design Structure Matrix

can share a material, spatial, energy, or information interface. More formally, a design structure matrix element

$$I_{r_{v_1} r_{v_2}}(\imath, \jmath) = 1 \tag{3}$$

if component $\imath$ of resource r_{v_1} exports energy or information to component $\jmath$ of resource r_{v_2}, and is zero otherwise [4]. This production design structure matrix I, in combination with the production knowledge base, will be used extensively to measure the effort of a reconfiguration process.

III. Development

In this section, the models of reconfiguration potential and ease are recombined in three steps so as to give a measure of the effort required for a reconfiguration process. First, the production knowledge base is used to measure the "magnitude" of a reconfiguration process. Next, the interfaces changed during the reconfiguration are assessed. These two measures assess factors intrinsic to the physical characteristics of the manufacturing system. In the third step, the method, used to realize the reconfiguration, is identified as an extrinsic factor on the effort of the reconfiguration process.

A. Magnitude of a Reconfiguration Process

The first step to assessing the effort required for a reconfiguration process is to assess its "magnitude". Ultimately, the larger the change is to the system, the large the required effort is to realize it. Consider a system $\mathcal{S}$ that goes through a reconfiguration process to become $\mathcal{S}$'. The associated sets of processes and resources $\{P, R\}$ will then be reconfigured to alternate sets $\{P', R'\}$ respectively. Such a reconfiguration will cause a change in the production knowledge base. Let the initial and final production knowledge bases J_S and J'_S respectively be of size $\sigma(\bar{P}) \times \sigma(\bar{R})$ where

$$\begin{aligned} \bar{P} &= P \cup P' \\ \bar{R} &= R \cup R' \end{aligned} \tag{4}$$

and $\sigma()$ is the "size of set" operator. For each knowledge base, element $J_S(w, v) = 1$ when a principal function [4], [6] $t_{w\pi}$ exists within the state machine N_{r_v} of resource r_v.

$$J_S(w, v) = \begin{cases} 1 & \text{if } t_{w\pi} \in N_{r_v} \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

Although, the two knowledge bases capture the system's capabilities before and after reconfiguration, a number of constraints may prevent their realization. They may be captured in binary constraint matrices K_S and K'_S of the same size. Intuitively, a constraint exists if any of the functions of the production process are not contained within the state machine of the corresponding resource.

$$K_S(w, v) = \begin{cases} 0 & \text{if } p_w \subseteq N_{r_v} \\ 1 & \text{otherwise} \end{cases} \tag{6}$$

The knowledge bases and their associated constraint matrices can be used to describe the system configuration as a loose collection of independent capabilities. Intuitively however, one knows that production processes must follow each other so that a product can be manufactured progressively on one resource than another. Pairs of consecutive capabilities have been modelled previously using a rheonomic production knowledge base J_ρ.

$$J_\rho = J_S \otimes J_S \tag{7}$$

where $\otimes$ is the Kronecker tensor product. As before, there may exist sequence-dependent constraints that eliminate certain pairs of consecutive capabilities. In order for one capability to follow another, the outputs of the former must be equivalent to the inputs of the latter. Quantitatively, the process p_w may be modeled with a petri-net [27] N_w

$$N_w = \{S_w, T_w, F_w\} \tag{8}$$

Its set of output places for the process is given by:

$$S_{wx} = \{s \in S_w | s^\bullet = \emptyset\} \tag{9}$$

while its set of input place is given by:

$$S_{we} = \{s \in S_w | {}^\bullet s = \emptyset\} \tag{10}$$

In order for a functional interface to occur, these input and output places must be equivalent and also be a part of the state machines of both the first and second resources. Formally,

$$K_\rho(\varrho, \psi) = \begin{cases} 0 & \text{if } S_{w_1 x} = S_{w_2 e} \subseteq (N_{r_{v_1}} \cap N_{r_{v_2}}) \\ 1 & \text{otherwise} \end{cases} \tag{11}$$

where $\varrho = \sigma(\bar{P})(w_1 - 1) + w_2$ and $\psi = \sigma(\bar{R})(v_1 - 1) + v_2$.

Together, the sequence dependent and independent flavors of the production knowledge bases and their constraint matrices may be used to model the production system configuration C.

$$C = [J_S \otimes (J_S \ominus K_S)] - K_\rho \tag{12}$$

This configuration model captures the productions system's capabilities while allowing the presence of both types of constraints. A reconfiguration process would act upon this configuration C and change it to an alternate configuration C'. Therefore, the magnitude of the reconfiguration process with respect to configuration change would be

$$\Delta C \quad = \quad XOR(C, C') \tag{13}$$

B. Interface Changes of a Reconfiguration Process

The next step in measuring the effort of a reconfiguration process is to quantify the interfaces changed. The initial and final production structure matrices I and I' respectively can be compared.

$$\Delta I = XOR(I, I') \tag{14}$$

where the two matrices may need to be padded with zero block matrices so as to reflect the combined set of resource $\bar{R}$.

This formulation, however, does not take into account the diversity of interface types in a production system. Pimmler and Eppinger have used a richer form of the design structure matrix to reflect multiple interface types [26]. Essentially, each design structure matrix element is replaced with a binary vector that differentiates between spatial, material, energy and information interfaces. Additionally, Covanich classifies interfaces by the method required for their reconfiguration but separates the different interface types into separate DSM's [28]. While this paper does not propose a specific classification of interface types, it reflects them with an additional parameter m in the design structure matrix $I_{r_{v_1} r_{v_2} m}(\imath, \jmath)$.

The design matrix can also be refactored to a different shape so that it may be more easily combined with other elements of the development.

$$\mathcal{I}(\sigma(\bar{R})(r_{v_1} - 1) + r_{v_2}, m) = \sum_{\imath} \sum_{\jmath} I_{r_{v_1} r_{v_2} m}(\imath, \jmath) \tag{15}$$

This simplification eliminates the need to keep track of interfaces between any pair of components in the manufacturing system by grouping them on the basis of the resource pair to which they belong. It also rewrites the DSM in column format rather than in square block matrix form. The next section will exploit this refactored form in terms of the interface changes between an initial and final configuration.

$$\Delta\mathcal{I}(\sigma(\bar{R})(r_{v_1} - 1) + r_{v_2}, m) = \sum_{\imath} \sum_{\jmath} \Delta I_{r_{v_1} r_{v_2} m}(\imath, \jmath) \tag{16}$$

C. Effort Required for a Reconfiguration Process

Once the two intrinsic factors that affect the effort required for a reconfiguration process have been developed, extrinsic factors are identified so that all three aspects may be combined. As mentioned in the previous section, interfaces may be differentiated based upon the energy or information that they transfer [22]. Alternatively, they may be classified based upon the method used to reconfigure them. For example, Covanich suggests that information interfaces should be classified on the basis of whether the interfaces require manual or automatic techniques for their reconfiguration [28]. These two opinions do not differ greatly as different energy exchanges would require different reconfiguration methods.

Each of these methods could result in dramatically different amounts of effort required for each interface. Hence, a "method difficulty vector" M is introduced. Its length accommodates the number of different reconfiguration methods identified. Its elements $M(k) \in (0, \infty)$ can be expressed in units of time or cost per interface. Determination of these values would ultimately have to be confirmed empirically after an appropriate interface classification system had been chosen. Considering the practical implications of such work, it is more like that the setting of such research would be the laboratory rather than case studies. Nevertheless, the utility of method difficulty vector to this development is that it explicitly separates the extrinsic factors of reconfiguration effort from the intrinsic ones.

Given these three factors, the effort of a reconfiguration process can be calculated.

$$\text{Reconfiguration Effort} = \left(\sum_{\varrho}^{\sigma^2(P)} \Delta C \right) * \Delta\mathcal{I} * M \tag{17}$$

Here, the magnitude of the reconfiguration process is weighted by the complexity of the interfaces changed which themselves are weighted by the difficulty of the method used in their reconfiguration. This equation simply shows that the effort required for a reconfiguration process can be minimized by

1) minimizing the changes in the system's capabilities
2) having more modular or less complex resource interfaces
3) using methods or tools (.e.g. automatic equipment) that facilitate the realization of the reconfiguration.

IV. Illustrative Example

A simplified reconfiguration analysis can now be carried out to illustrate the developments of the previous section. A conceptualized manufacturing system based upon the milling department of a leading machine-tool maker is taken as an example. It consists of two milling machines accessed by two loading robots on a circular track. As seen in Figure 5, the addition of a third milling machine is taken as a reconfiguration.

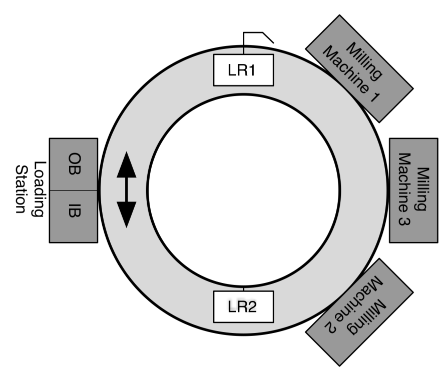

Fig. 5. A Conceptualized Manufacturing System

The control structure, shown in Figure 6, straightforwardly employs an execution program and a physical agent for each resource. These agents communicate through and register themselves to a facilitator/message broker [12], [29]. Normally such a system would use product agents [15] for coordination but they are not shown as they are not part of this analysis. Using a reconfigurability measurement method described elsewhere [4], [18], the production design structure matrix and knowledge base can be found straightforwardly. Figure 7 shows the two matrices of the system after reconfiguration as blackened elements. Meanwhile, elements changed during

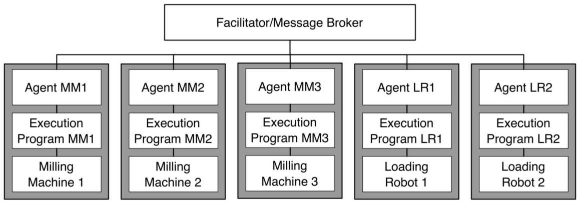

Fig. 6. Conceptualized Control Structure

the reconfiguration are shown as grey "1"s. Note that the block corresponding to the added milling machine is colored black to reflect that it is a pure copy of the other two milling machines.

From these two models, the reconfiguration effort can be calculated using the method described in Section III. J_ρ is calculated straightforwardly but care must be taken to include the minimal rheonomic constraints in K_ρ [4], [6]. At this stage, the matrix difficulty vector is set to unity. However, further component decompositions [4], [19] can allow interface types to be more finely classified. The calculated result is 120 reconfiguration effort units. Gaining an intuitive sense of the relative size of this value ultimately requires a standardization effort of the definition of production processes, interfaces, and the associated reconfiguration processes [4]. However, this measure does exist on a rational scale [30] and hence a wide variety of comparison statistics (e.g. averages, percentages) can be applied validly. Furthermore, the reconfiguration effort is expressed in the intuitively appealing units of [time*processes/resource].

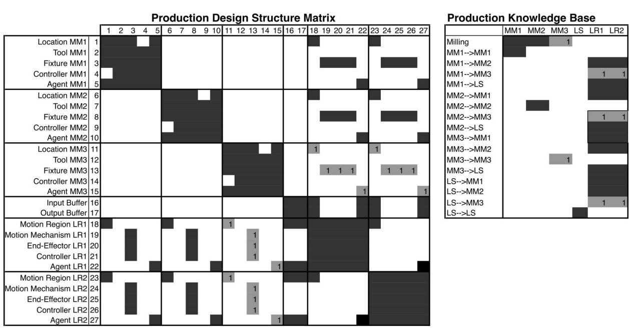

Fig. 7. Production DSM and Knowledge Base

V. Discussion

The measure of reconfiguration effort found in Equation 17 leads to a number of implications on adjacent research. This section discusses some of these with respect to three topics: integrability, easy reconfiguration by resource change, and finally easy reconfiguration by component change.

A. Integrability: A Key Characteristic of Reconfigurability

Integrability has been identified recently as the second of five key characteristics of reconfigurability. Mehrabi [31] defined it as:

Definition 5.1: Integrability – The ability with which systems and components maybe readily integrated and future technology introduced.

Furthermore, a quantitative measure for it has been given as:

$$\mathcal{I} = \sum_{\psi}^{\sigma^2(R)} \left[1 - \frac{\bar{a}_{o\psi}}{\bar{\mathcal{V}}_{o\psi}}\right] \sum_{\varrho}^{\sigma^2(P)} [J_\rho \ominus K_\rho](\varrho, \psi) \tag{18}$$

where $\bar{a}_{o\psi}$ is the sum of the non-zero elements in the off-block diagonals in production design structure matrix, and $\bar{\mathcal{V}}_{o\psi}$ is the size of that area as measured in components[2] [4].

This measure very strongly corresponds to the reconfiguration effort measure shown in Equation 17. First of all, the integrability measure neglects the sequence-independent constraints matrix K_S but essentially uses the same configuration model. Next, the integrability measure is founded upon the key characteristic of modularity [4], [31]. Hence, it weights the configuration model by the modularity term $\bar{a}_{o\psi}/\bar{\mathcal{V}}_{o\psi}$ rather than simply the number of inter-resource interfaces $\bar{a}_{o\psi}$. The measure also slopes negatively from a maximal value to take into account that it measures an ability rather than an effort. Finally, the measure does not differentiate between the types of interfaces and so forces $M = 1$. Considering these differences, it can be shown straightforwardly that the term

$$\mathcal{I} = \sum_{\psi}^{\sigma^2(R)} \bar{a}_{o\psi} \sum_{\varrho}^{\sigma^2(P)} [J_\rho \ominus K_\rho](\varrho, \psi) \tag{19}$$

is associated with a reconfiguration process where $K_S = \mathbf{0}$, $\Delta C = C$, $M = 1$, and

$$\Delta I = \begin{cases} I & \text{if } v_1 \neq v_2 \\ 0 & \text{otherwise} \end{cases} \tag{20}$$

These conditions correspond to a reconfiguration where interface types are not differentiated and the system is purely decoupled without any change to resource's components. Therefore, this measure is most useful in applications where the resources and all of their associated control software are pre-configured and do not require configuration prior to their integration.

B. Easy Reconfiguration by Resource Change

One strategy for reconfiguration is the addition, removal, or replacement of resources. Consider the introduction of a new resource. Its immediate affect would be to add a column's worth of capabilities to the J_S knowledge base. J_S would also require additional rows if this resource introduced non-redundant production processes. These changes to the production capabilites would presumably have their production strategy and operation reasons and hence should be considered fixed. However, the associated changes to the production design structure matrix could be a matter of design optimization.

When a new resource is added, an additional block row and column are added to the DSM. In such a case, Equation 17 suggests that reconfiguration effort is minimized when 1.) the resource's interfaces at all control levels are as modular as possible 2.)the resource's state machine requires a minimal amount of additional configuration effort. The first strategy minimizes the filled elements in the DSM's off-block diagonal. Numerous technical strategies have been developed for this purpose. Notably, the distributed manufacturing system design approaches [1]–[3], [11] specifically try to minimize the number of messages passed between physical agents. The second strategy minimizes the changed elements in the block diagonal associated with the added resource.

Traditionally, this configuration effort has been measured using cyclomatic [30] and strategic complexity [32] measures. Interestingly, the number of changed elements in the block diagonal corresponds closely to the latter of these. The strategic complexity $\mathcal{CS}$ of a state machine N_{r_v} is given by:

$$\mathcal{CS}(N_{r_v}) = \sigma(S_{r_v}) + \sigma(T_{r_v}) + \sigma(F_{r_v}) \tag{21}$$

where $\sigma(S_{r_v})$, $\sigma(T_{r_v})$, $\sigma(F_{r_v})$ are the number of places, transitions and arcs respectively of N_{r_v} expressed as a petri-net. Assuming that the net is pure [33], it will have an incidence matrix $\mathcal{A}$

$$\mathcal{A} = A_+ - A_- \tag{22}$$

where $A_+(i,j) = t_i \times s_j$ and $A_-(i,j) = s_j \times t_i$. Using the methodology that the net's places are chosen to correspond to the resource's components, the resource's block diagonal portion of the DSM becomes

$$I_{r_v r_v} = \mathbf{1} + A_-^T A_+ \tag{23}$$

Using this result, the growth of the two measures with respect to the number of places can be compared. Table I compares the strategic complexity of a resource's petri net to its number of full block diagonal DSM elements for the cases of fully serial and fully coupled resource nets. While this result concludes

TABLE I
CORRESPONDENCE OF DSM TO STRATEGIC COMPLEXITY

	Fully Serial	**Fully Coupled**
DSM	$2n-1$	n^2
$\mathcal{SC}$	$4n-3$	$6n^2-5n$

that the two measures do not form a rational scale [30] with respect to each other, the order is the same thus facilitating their use as comparable measures of the same property. Efforts to minimize one measure prior to a reconfiguration will similarly affect the other and vice versa.

C. Easy Reconfiguration by Component Change

The second and perhaps simpler strategy for easy reconfiguration is to add, remove, or replace only a few components rather than a whole resource. A component replacement, for example, can replace the principal function of a capability so that a filled element in the knowledge base J_S is moved to another row in the same column. Similarly, a component replacement can remove constraints and introduce others resulting in a similar effect on the production configuration C. Industrial examples of these reconfigurations are many. A simple tool or fixture change would be represented in this way. Additionally, control software can be replaced so as eliminate constraints. A technical planning system can be rewritten to enable all of the production system's capabilities. Meanwhile, scheduling and execution control systems can be written "flexibly" rather than monolithically to eliminate sequence-dependent constraints [4], [6], [34]. While this type of reconfiguration may not always be able to achieve as dramatic a change in a production system's capabilities, its utility is that ΔI is potentially very small and hence a relatively small reconfiguration effort may be needed.

Such reconfigurations are particularly interesting when special techniques are developed to improve the method of reconfiguration described in the method difficulty vector M. The case of "single-minute-exchange-of-dye" technology may be classified as such a technique. Along the same line, tool changers and track gates can be viewed as automated techniques to reduce the time and effort of the reconfiguration method. In such a way, they may be classified as some of the earliest "self-reconfiguring" production systems [35]. Furthermore, ongoing developments to apply multi-agent systems to "self-reconfiguring" production systems can be similarly classified albeit for the domain of information technology.

These easy reconfiguration techniques can shed some light on the "reconfigurable vs. flexible" manufacturing system debate [36]. Flexible manufacturing systems often realize reconfigurations by component change with a modicum of effort. For this reason, they appear to have multiple capabilities simultaneously. A "flexible" machine tool, for example, may have a cache of one hundred tools which it can choose from at will. Such a system can be viewed as having a rather dense knowledge base J_S over a strategic time span. Alternatively, it may be perceived as having an instantaneously sparse J_S with a small matrix difficulty vector M for certain types of interfaces. In either case, this ability to realize reconfigurations easily by component change does not guarantee that it is truly reconfigurable because reconfigurations by resource change may remain very difficult to achieve. This second type of reconfiguration remains a challenge for many "flexible manufacturing systems" and in the subject of ongoing research [28].

VI. CONCLUSIONS AND FUTURE WORK

This paper presented a measure of reconfiguration process effort. It did this by recombining previously completed work on the measurement of reconfiguration potential and ease. Each of these were presented first as intuitive notions and then subsequently modeled. Next, a measure of reconfiguration process effort was developed. It showed that this effort can be minimized by:

1) minimizing the changes in the system's capabilities
2) having more modular or less complex resource interfaces
3) using methods or tools (e.g. automatic equipment) that facilitate the realization of the reconfiguration

This development led to a number of implications on adjacent research. First, the previously proposed integrability measure was shown to correspond strongly to this measure of reconfiguration process effort. Specifically, the integrability measure was shown to correspond to a reconfiguration where interface types are not differentiated, and the system is purely decoupled without any change to the resources' components. The measure of reconfiguration effort also showed how modular resource interfaces, and non-complex control structures facilitate the introduction of new resources. Finally, the measure showed how reconfigurations can be achieved easily by modularizing components such as tools and fixtures. It thus showed an approach for designing "self-reconfiguring" production systems and demonstrated how "Flexible Manufacturing Systems" can be reconfigurable without necessarily being able to easily add new production resources.

In many ways, this paper represents the coherent integration of much previous work on the subject of reconfigurability measurement [4]–[7], [18], [24], [25], [28], [34], [37]. Collectively, this work has identified a number of avenues for future work. At the most basic level, reconfigurability measurement requires the quantization of production processes, resources, and their associated components. There exists no such standard that defines these units and hence future work in this domain will demand the rigorous development of production system ontologies. Next, much experience can be gained in measuring the reconfigurability of existing production systems. While initial case stuides have been reported [4], [28], [37], future work will require two types of case studies. The first is the measurement of reconfigurability as a structural property to predict the relative cost or time of a class of reconfigurations. The second is the measurement of reconfiguration process effort as compared to the actual time/cost necessary to realize the reconfiguration process. While either research can be completed on industrial scale systems, laboratory or prototype production systems would prove more practical given the downtime associated with the research methodology. Finally, this work would be ultimately integrated improvement in the design process of reconfigurable manufacturing systems.

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