

Facilitating Ease of System Reconfiguration through Measures of Manufacturing Modularity

Amro M. Farid

ABSTRACT

In recent years, many design approaches have been developed for automated manufacturing systems in the fields of reconfigurable manufacturing systems (RMS), holonic manufacturing systems (HMS), and multi-agent systems (MAS). One of the principle reasons for these developments has been to enhance the reconfigurability of a manufacturing system; allowing it to readily adapt to changes over time. However, to date reconfigurability assessment has been limited. Hence the efficacy of these design approaches remains inconclusive. This paper is the second of two in this issue to address reconfigurability measurement. Specifically, “reconfiguration ease” has often been qualitatively argued to depend on the system’s modularity [1], [2]. For this purpose, this paper develops modularity measures in a three step approach. First, the nature of typical manufacturing system interfaces are discussed. Next, the qualitative understanding underlying existing modularity measures is distilled. Finally, these understandings are synthesized for a manufacturing system context. This approach forms the second of two pillars that together lay the foundation for an integrated reconfigurability measurement process described elsewhere [3]–[9]

I. INTRODUCTION

In the 1990’s the global marketplace has necessitated the production of mass-customized products of increasingly short product life cycle [10], [11]. 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.

Definition I.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 last decade, many technologies and design approaches have been developed to enable reconfigurability in

manufacturing systems [12], [13]. These have included modular machine tools [14], distributed automation [15], [16], multi-agent systems [17], [18] and holonic manufacturing systems [19]–[21]. While initial efforts to assess these design approaches have been reported [22]–[25], numerous authors have identified the need for a holistic reconfigurability measurement process [7], [26]–[31]. Hence, it remains inconclusive whether the resulting designs achieve their intended level of reconfigurability. This paper is the second of two in this issue that propose elements of an integrated reconfigurability measurement process based upon the complementary principles of reconfiguration potential [5], [7]–[9] and reconfiguration ease [3], [4], [6], [7], [32]. The latter of these has already been qualitatively argued to depend on the system’s modularity [1], [2]. Hence, this paper seeks to address reconfiguration ease by developing a new set of quantitative manufacturing modularity measures.

A three part discussion is followed. Section 2 provides the background material necessary for their development. Next, Section 3 develops manufacturing modularity as measures of reconfiguration ease. Section 4 concludes with the measures’ application to an illustrative example. Prior to proceeding, this paper restricts its discussion to the shop-floor activities of automated manufacturing system as defined in Levels 0-3 of ISA-S95 [33]. Furthermore, it defines reconfigurability as

Definition I.2. Reconfigurability [6], [7]: 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.

Furthermore, the research scope is restricted to two classes of reconfigurations: 1.) changes in the number and type of production resources and 2.) changes in the number and type of product variants.

II. BACKGROUND

This section provides the background material for the development of manufacturing modularity measures in four parts. First, measurement processes are discussed in general. Next, design structure matrices are introduced as a model often used in the study of system modularity. Thirdly, a manufacturing system specific version of the DSM is described. The section concludes with a discussion of existing modularity measures.

A. Measurement Processes

Generally speaking, a measurement process requires:

- 1) Identification of measurables
- 2) Methods for measuring the measurables

- 3) Models for describing/modeling system
- 4) Identification of structure dependent properties
- 5) Formulaic measures of relating those models to those properties

The requirements can be graphically represented as a sequential data flow diagram in Figure 1. Implicitly, as an



Figure 1. A Generic Measurement Process

objective, a set of measured properties need to be identified. In most measurement processes, these properties are distinct from the system measurables which must be extracted from the system of interest with a set of measurement methods. If the measured property is too complex for direct measurement, the measurement must be inferred [34]. This requires that the measurables be related using a set of models. Finally, the mathematical theory of measurement [35] requires a set of measures. These measures are a specific class of mathematical functions and serve to convert related measurables to the final measured property [36].

B. Design Structure Matrix

One model often used in the measurement of system modularity is the design structure matrix (DSM). It is a systems analysis tool that captures the interactions, interdependencies, and interfaces between components of a complex system in a compact and clear representation [37]. Given two components A and B, they may interact in a parallel, sequential or coupled fashion. These interactions may be spatial, structural, energy, material or information interfaces [38]. Figure 2 shows the graphical representation of these interactions and their associated design structure matrices. Essentially, off-diagonal

Three Configurations of a System																														
Relationship	Parallel	Sequential	Coupled																											
Graph Representation																														
DSM Representation	<table border="1"> <tr><td></td><td>A</td><td>B</td></tr> <tr><td>A</td><td></td><td></td></tr> <tr><td>B</td><td></td><td></td></tr> </table>		A	B	A			B			<table border="1"> <tr><td></td><td>A</td><td>B</td></tr> <tr><td>A</td><td></td><td></td></tr> <tr><td>B</td><td>X</td><td></td></tr> </table>		A	B	A			B	X		<table border="1"> <tr><td></td><td>A</td><td>B</td></tr> <tr><td>A</td><td></td><td>X</td></tr> <tr><td>B</td><td>X</td><td></td></tr> </table>		A	B	A		X	B	X	
	A	B																												
A																														
B																														
	A	B																												
A																														
B	X																													
	A	B																												
A		X																												
B	X																													

Figure 2. DSM Representations of System Configurations [37]

elements reflect interaction. The placement of an off-diagonal “X” represents the existence of an interaction between two components A and B [37]. Some authors, however, have replaced the “X” with numerical values in order to subjectively assess the strength of a particular interaction [39], [40]. The DSM is formally described in [41] and a comprehensive tutorial with accompanying application can be found at [7], [37].

The design structure matrix has already been applied in numerous works which indicate its applicability to the study of reconfigurability in manufacturing systems. Its application to automotive climate control systems [39] and large commercial

aircraft engines [38] allows an analogy to be drawn between the cross-energy domain transportive and transforming functions of an aircraft engine to those of manufacturing systems. It has also been used to facilitate the realization of highly customized products [42] and their platforms [43]. A reconfigurable manufacturing system, in a sense, is a system that undergoes customization over time much like a customized product line. Finally, the model has found application in product life cycle engineering [40], [44] and hence may play a role in the efficient maintenance and decommissioning of manufacturing systems.

C. Production Design Structure Matrix

Most recently, the Production Design Structure Matrix has been developed as a DSM specific to production. Its method of application and case studies are described elsewhere [3]–[7] and only its essential elements are described here. To begin, the inherently open manufacturing system must be translated to an analogous closed one. Manufacturing systems composed of four types of resources *R* (value-adding machines *M*, material handlers *H*, independent buffers *B*, and centralized controllers *Q*) convert information, energy, and material into other forms. Furthermore, the product line *L* is included as an intrinsic part of the analogous closed system. Depending on the application, these products may adhere to the intelligent product paradigm [45]. Additionally, the system boundary acts as an infinite source of the necessary system inputs and an infinite sink to the generated outputs. The system boundary also serves as a common platform to which all the manufacturing system components can connect. For example, basic factory services such as power and networking are included as part of the system boundary. Interactions between two manufacturing system components via the system boundary are treated as direct. Given these subsystems, Figure 3(a) shows the production DSM of a distributed manufacturing with one of each type of production resource while Figure 3(b) adds a centralized controller to the subsystems list.

These subsystems can then be decomposed into constituent components using an interface-based method of stepwise refinement [6], [7]. In order to systematize the first iteration of this step-wise method, typical components can be identified for each of the previously defined subsystems.

a) *Transforming Machine Components*: A machine must have a tool and a fixture to form and hold the product respectively. These two components may be simple, or they may be treated as aggregations with their own set of subordinate components. For example, a machine may be composed of complex fixturing and tooling systems that flexibly allow for multiple configurations of tools and fixtures. Additionally, the machine must have control components. Depending on the degree of distribution in the manufacturing system, these can include controllers devoted to continuous real-time, execution, scheduling or planning. Implicitly, the machine must also have a location by which to relate itself spatially to the other manufacturing subsystems. Although the machine location is not strictly speaking a machine component, it, like the other components, can be specified as a set of scalar parameters

	Products	Machines	Material Handlers	Buffers
Products	I_{LL}	I_{LM}	I_{LH}	I_{LB}
Machines	I_{ML}	I_{MM}	I_{MH}	I_{MB}
Material Handlers	I_{HL}	I_{HM}	I_{HH}	I_{HB}
Buffers	I_{BL}	I_{BM}	I_{BH}	I_{BB}

(a) Without Centralized Controllers

	Products	Machines	Material Handlers	Buffers	Central Controllers
Products	I_{LL}	I_{LM}	I_{LH}	I_{LB}	I_{LQ}
Machines	I_{ML}	I_{MM}	I_{MH}	I_{MB}	I_{MQ}
Material Handlers	I_{HL}	I_{HM}	I_{HH}	I_{HB}	I_{HQ}
Buffers	I_{BL}	I_{BM}	I_{BH}	I_{BB}	I_{BQ}
Centralized Controllers	I_{QL}	I_{QM}	I_{QH}	I_{QB}	I_{QQ}

(b) With Centralized Controllers

Figure 3. Production System Design Structure Matrix

pertaining to the machine. The set of machine components is then

$$C_m = \{\text{Location, Tool(s), Fixture(s), Controllers}\} \quad (1)$$

b) *Material Handling Components:* Material handler components can be treated similarly. A material handler must have an end-effector with an associated motion mechanism to move and hold the product. Additionally, the material handler must have controllers devoted to continuous real-time, execution, scheduling or planning. Implicitly, the machine must also have a region of motion by which to relate itself spatially to the other manufacturing subsystems. The set of material handling components is then

$$C_q = \left\{ \begin{array}{l} \text{Motion Region, Motion Mechanism,} \\ \text{End-Effectors(s), Controllers} \end{array} \right\} \quad (2)$$

c) *Independent Buffer Components:* Independent buffers have a subset of the functionality of machines in that they must store/hold a product but not form it. Assuming that the independent buffer requires active control and has finite capacity, the set of independent buffer components is then

$$C_b = \{\text{Location, Fixture(s), Controllers}\} \quad (3)$$

d) *Centralized Controller Components:* Determining the components of a centralized controller is a non-trivial task. However, their determination is facilitated by two primary questions. First, the scope of control needs to be determined. Any given controller can be divided into the control of transformation and transportation control activities. Next, the controller can be decomposed into the different types of control functions such as execution, scheduling and planning. A centralized controller may have one or more of these components and so one possible aggregation of its is:

$$C_q = \left\{ \begin{array}{l} \text{Transformation Execution Controller,} \\ \text{Transportation Execution Controller,} \\ \text{Transformation Scheduling \& Planning Controller,} \\ \text{Transportation Scheduling \& Planning Controller} \end{array} \right\} \quad (4)$$

e) *Product Components:* The list of product components can be as simple as a bill of material for assembled products. For non-assembled products, a further level of detail can be used by considering each product feature as a component. Such features may include slots, holes or chamfers. Also, given intelligent products or part-oriented control, a number of intelligent software components are needed to control the planning and scheduling activities of the various subassemblies. The intelligent product components set is:

$$C_l = \{\text{Parts/Features, Intelligent Software(s)}\} \quad (5)$$

Once the subsystem component lists have been identified, the interfaces between them can be captured into the production DSM. For this purpose, CAD/CAM data, process plans, UML diagrams can all be included [3], [4], [6], [7]. High level interfaces can be identified first and then characterized in increasing detail as the components lists are decomposed further in a step-wise fashion [6], [7]. More detailed methods prescribing the types of information to be included in the method have been presented previously and continue to be the subject of ongoing research [?], [6], [7].

D. Limitations of Existing Measures for Manufacturing Systems

The next step in a modularity measurement process requires a modularity measure that draws upon the production DSM. Unfortunately, according to the most recent modularity literature review, there is no consensus on the property's definition, and in one experiment, results showed no statistical significance in the modularity ranking that a group of product-design graduate students assigned to a group of products [46]. Clearly, developing a rational or absolute scale [47] measure under these conditions would have limited benefit because the underlying *intuitive* concept is not well-understood. Stated another way, the *current* understanding of modularity does not

fulfill the measurement axioms [47]. Despite these difficulties, the importance of modularity to system structure is clear and its impact on reconfigurability as the first and primary key characteristic [48] is well accepted. As a result, the author agrees with Gershenson [46] that “there is an obvious need for further research in product modularity”.

To proceed from this impasse, the intuitive understanding behind some of the literature’s modularity measures are assumed to be true for use in the following section. Meanwhile, some of the quantitative limitations of these measures are highlighted.

- **Subjective Assignment of Interaction Values** Many measures fill the elements of the DSM with values that are subjectively assessed [40], [49]–[51]. Therefore, the resulting measures at best form an ordinal scale [47].
- **Dependence on Discipline Specific Variables** Many of the measures provided in the literature depend on variables that are specific to a particular discipline and not applicable to the reconfiguration of manufacturing systems. These include the manufacturing process used to produce the product [49] [40], and the differentiation between the types of information exchanged between software modules [52]–[58].
- **Inconsistent Units** Some measures do not combine units in mathematically acceptable ways [42], [59], [60].
- **Interchangeability of Modularity and Complexity Measures** Many measures used to describe modularity are complexity measures [36] [47]. The relationship between the two is not immediately transparent.
- **Lack of Consideration for Module Cohesion** Some measures do not account for module cohesion (intra-module interaction) [51], [61], [62].

In addition to these limitations, it remains unclear how to compare two independent systems using many of these measures. Most measures allow for a given system’s modularity to be improved incrementally or optimized, but do not allow for its modularity to be compared to an entirely different system. The developments of the next section will seek to address each of these limitations.

III. MANUFACTURING MODULARITY MEASURES

Given the limitations of existing modularity measures, the development of a new set of manufacturing modularity measures can be attempted. A three step process is followed. First, the nature of typical manufacturing system interfaces are discussed. Next, the qualitative understanding behind the previously discussed measures is distilled. Finally, a new set of modularity measures are presented.

A. Manufacturing System Interfaces

Throughout the literature, modularity is dependent on the complexity of the interface between two subsystems [49]. Hence, the typical complexity in manufacturing system interfaces needs to be better understood. The first complicating factor is that the nature of the interface changes dramatically at each of the levels of a manufacturing system [1]. Figure 4 shows some of the typical interfaces at the various levels

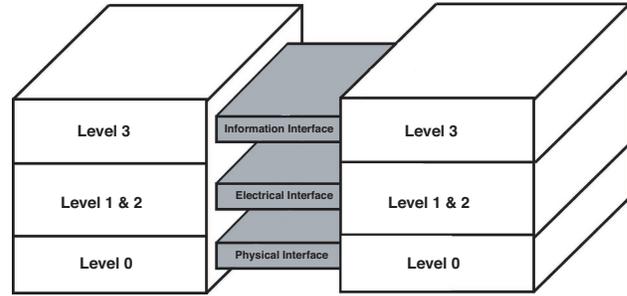


Figure 4. Multi-level Interfaces of Production Resources

of the production system. At the lowest level, the physical process occurs; often a long 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. Each of these energy domains typically has its own modeling techniques associated with a specific engineering discipline.

To overcome this multi-disciplinary problem of interface complexity, this work adopts the method commonly used in both the software engineering [56], [63] and product design fields [42], [49], [51], [64]. Each interface can be described by a number of parameters, and the larger this number is, the more complex the interface is [47]. This approach is particularly reasonable because object-oriented software is often built to model the structure and the behavior of physical objects [65]. Figure 5(a) shows the reconfiguration of such a multi-parametered inter-resource interface. Specifically, the ease of reconfiguring two resources R_1 and R_2 which realize production processes P_2 and P_3 can be said to increase as the number of parameters required to describe their shared interface increases.

The effort associated with reconfiguring two resources, as previously shown in Figure 5(a), is further complicated with the addition of centralized controllers (e.g. PLC’s, centralized schedulers/dispatchers). Figure 5(b) shows the various interfaces that arise when a centralized controller is introduced. As before, an interface exists between the two resources. Additionally, there now exists an interface between the centralized controller and each of the primary resources. It ensures that each resource is able to complete its associated processes. This interface is typically put together once upon first installation and pulled apart once upon decommissioning. Resource rearrangements address these interfaces more rarely. Finally, there is an intra-resource interface within the centralized controller that describes where the rest of the functionality for the first resource interfaces with the rest of the functionality for the second resource. The effort required to pull apart or put-together this intra-resource interface may be considerable as intra-resource interfaces are typically more complex than inter-resource ones. In summary, there are three types of interfaces

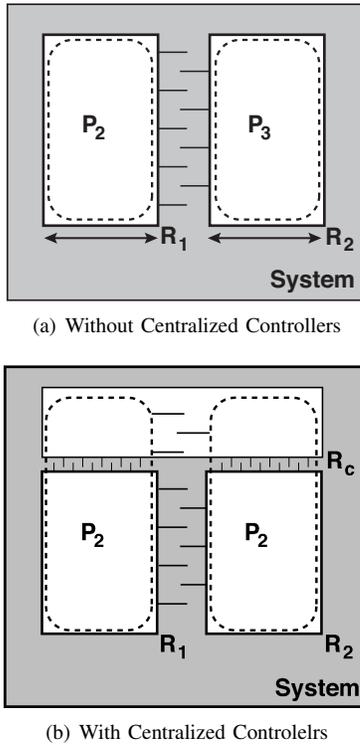


Figure 5. Multi-Parametered Resource Interfaces

that affect the resources' reconfiguration which all add to the effort required.

- Type I: Primary Resource to Primary Resource
- Type II: Primary Resource to Secondary Resource
- Type III: Intra-Secondary Resource Interface

These specific characteristics of manufacturing systems (in addition to the limitations described previously in Section 2.4) must be taken into account in the development of a manufacturing modularity measure.

B. Understanding Modularity Qualitatively

These typical manufacturing system interfaces may be captured into a production DSM but the measurement process would not be complete without a modularity measure. Given the insufficiency of the modularity measures presented in the literature, the discussion must return to the qualitative understanding of the property. The strategy for the redevelopment of the understanding consists of three elements: 1.) common and mutually agreeing understanding behind the presented modularity measures are incorporated. 2.) the DSM is imposed as a conceptual framework to organize these elements. 3.) each understanding is presented in terms of a comparison scenario and described graphically with its associated pair of design structure matrices.

Before describing these comparison scenarios, it is important to note that any discussion of the DSM can be framed in terms of six variables. They are: 1.) Total Coupling (inter-subsystem interaction) (a_o), 2.) Total Cohesion (intra-subsystem interaction) (a_d), 3.) Total Behavior (a) 4.) Total Possible Inter-subsystem Interaction (\mathcal{V}_o), 5.) Total Possible

Intra-subsystem Interaction (\mathcal{V}_d), and 6.) Total Possible Interaction (\mathcal{V}). These variables adhere to two constraints:

$$\begin{aligned} \mathcal{V} &= \mathcal{V}_d + \mathcal{V}_o \\ a &= a_d + a_o \end{aligned} \quad (6)$$

As a result, modularity (or any property that uses the DSM) can have no more than four independent comparison scenarios each of which vary exactly one of these variables. Four independent comparison scenarios are now presented based upon their support in the literature.

1) *Scenario I: Greater Coupling, Ceteris Paribus*: As a baseline scenario, if a system \mathcal{S}_1 has greater coupling than a system \mathcal{S}_2 of equal behavior and equal number of subsystems and components, then \mathcal{S}_2 is more modular than \mathcal{S}_1 [49], [52]–[54], [56], [61] [39], [40], [42], [50], [51], [57]–[60], [62], [66]–[69]. As seen in Figure 6, \mathcal{S}_1 and \mathcal{S}_2 would have DSM's of the same size and density but \mathcal{S}_1 would have more of its interactions in the off-block diagonal regions.

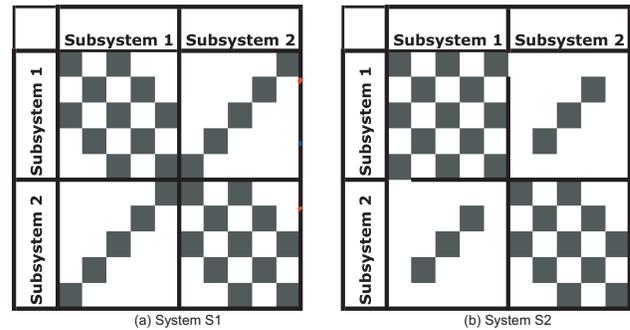


Figure 6. Scenario I Design Structure Matrices: Greater Coupling

2) *Scenario II: Greater Cohesion, Ceteris Paribus*: If a system \mathcal{S}_1 has greater cohesion than a system \mathcal{S}_2 of equal number of subsystems, components and coupling, then \mathcal{S}_1 is more modular than \mathcal{S}_2 [42], [52], [56], [57], [59], [60], [66], [67], [69]. As seen in Figure 7, \mathcal{S}_1 and \mathcal{S}_2 would have DSM's of the same size, and same number of interactions on the off-block diagonal. However, \mathcal{S}_1 would be comparatively more dense along its block diagonal.

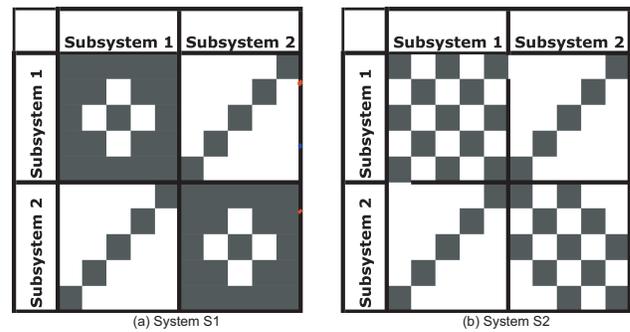


Figure 7. Scenario II Design Structure Matrices: Greater Cohesion

3) *Scenario III: Greater Total Number of Modules, Ceteris Paribus*: If a system \mathcal{S}_2 has a greater number of modules than a system \mathcal{S}_1 of equal behavior, then \mathcal{S}_2 is more modular [52]. While this understanding has only been explicitly stated

in one measure, it has been implied many times elsewhere. Many references emphasize that each module have exactly one function [39], [68], [70]–[75]. If the system behavior is held constant, this implies that the number of modules be increased until it reaches the ideal of one function per module. From the perspective of the DSM, this understanding would cause system \mathcal{S}_2 to have a comparatively more dense block diagonal and hence would be more cohesive. As seen in Figure 8, \mathcal{S}_2 has a DSM with more well formed modules.

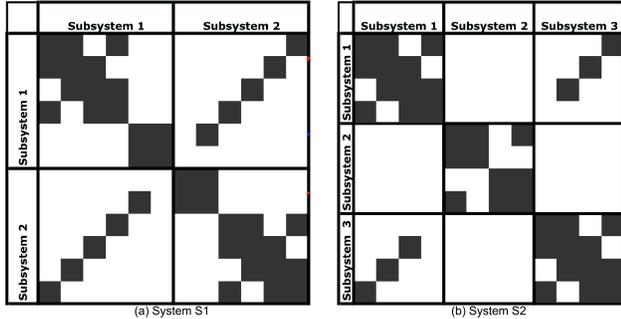


Figure 8. Scenario III Design Structure Matrices: Greater Number of Modules

4) *Scenario IV: Greater Distribution of Subsystem Size, Ceteris Paribus:* If a system \mathcal{S}_2 has a greater distribution of subsystem sizes than a system \mathcal{S}_1 of equal behavior, and number of components, then \mathcal{S}_1 is more modular. This last comparison scenario is *asserted* without literature support. The rationale, from an abstract DSM-based point of view is that the system with greater distribution of subsystem sizes is going to have more densely coupled subsystems. As a result, the relative coupling is greater, and the modularity should decrease accordingly. As seen in Figure 9, \mathcal{S}_2 has a more dense off-block diagonal. More concretely, one can imagine a PLC that is responsible for the coordination (Level 3) and actuation (Level 2) of a track gate. The actuation control requires a large number of sensor inputs in the vicinity of the track gate. The system would be more modular if actuation control were included as part of the track gate so that only a small amount of information is passed between the PLC and the gate.

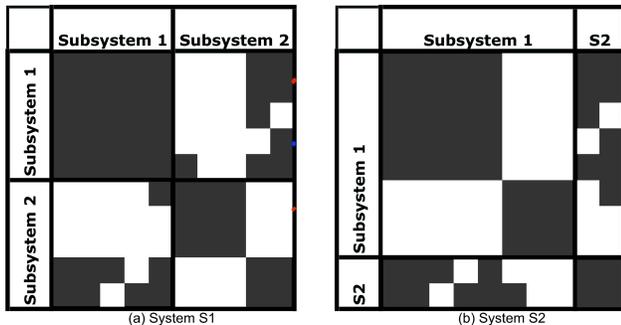


Figure 9. Scenario IV Design Structure Matrices: Greater Distribution of Subsystem Size

5) *The Modularity-Density Analogy:* The past four comparison scenarios and their associated figures suggest that the literature collectively intuits modularity as a property that resembles “planar mass density” (mass per unit area), where

the “mass-density” in the block-diagonal regions of the DSM need to be maximized and the “mass-density” in the off-block diagonal regions need to be minimized. The six previously defined variables of the DSM are given their analogs in Table I. Stated differently, this intuition gives:

$$\begin{aligned} d\Gamma/da_o &< 0 & d\Gamma/da_d &> 0 \\ d\Gamma/d\mathcal{V}_o &> 0 & d\Gamma/d\mathcal{V}_d &< 0 \end{aligned} \quad (7)$$

where Γ is modularity.

C. Quantitative Measures

The planar mass density analogue gives a strong basis for the proposal of a modularity measure. There is a negative relationship between modularity and the density of the off-block diagonal and a positive one with the block-diagonal. Hence, their difference can be used to measure modularity Γ :

$$\Gamma = \left[\frac{a_d}{\mathcal{V}_d} \right] - \left[\frac{a_o}{\mathcal{V}_o} \right] \quad (8)$$

where each of the variables is given in Table II. These variables are based upon the interface matrix $I_{\varsigma_1\varsigma_2}(\iota, j)$, where ς_1 and ς_2 are indices for two subsystems, and ι and j are indices for two of their components.

This function makes a likely candidate for the measurement of modularity. It fulfills the intuition developed in the previous section and summarized in Equation 7. The measure also typically gives values on the interval [0,1]. In the degenerate scenario that the off-block diagonal is denser than the block-diagonal, the measure gives negative values. The measure also reaches its maximal value of unity when the off-block diagonal is empty and the block-diagonal is entirely full. It also introduces a level of objectivity and consistency because any DSM is characterized by six variables ($a, a_o, a_d, \mathcal{V}, \mathcal{V}_o, \mathcal{V}_d$) with two constraints. The usage of four variable in the measure hence completely characterizes the measured system in comparison to another. Finally, it introduces the intuitively appealing units of interactions/components². Therefore, particularly dense regions of the DSM immediately reflect a great deal of coupling or cohesion between its associated components.

This modularity measure is also sufficient to measure re-configuration ease even though the two concepts are not equivalent. In the intuitive description given in Figure 5(a) re-configuration ease had no dependence on cohesion but strongly depended on minimal subsystem interaction. If each subsystem is treated as a fully-functional unit, then the effort *required* to integrate it into the rest of the system should be proportional to the number of couplings that must be addressed. The effort *saved* from integration should therefore be a negative linear relationship with the number of couplings starting from some theoretical maximum associated with a perfectly uncoupled system. The measure fulfills this intuition with the $-(a/\mathcal{V}_o)$ term. Thus, a pure a reconfiguration ease measure can be given as $1 - (a/\mathcal{V}_o)$.

This picture of integration is most plausible if the system is composed of only products and resources. In such a case, the resource boundaries are equivalent to process boundaries and only a single interface exists between any two subsystems. Integration becomes a task of ensuring that

Table I
 MODULARITY DENSITY ANALOGY

Modularity Term	Density Term	Symbol
Coupling	Off-Block Diagonal Mass	a_o
Cohesion	Block-Diagonal Mass	a_d
Total System Interaction	Total Mass	a
Total Possible Inter-Subsystem Interaction	Off-Block Diagonal Area	\mathcal{V}_o
Total Possible Intra-Subsystem Interaction	Block Diagonal Area	\mathcal{V}_d
System Size	Total Area	\mathcal{V}

 Table II
 CONVENTIONAL EXPANSION OF MODULARITY VARIABLES

$a_d = \sum_{s_1}^{\sigma(S)} \sum_{i}^{\sigma(C_{s_1})} \sum_{j}^{\sigma(C_{s_1})} I_{s_1 s_1}(i, j)$	$a_o = \sum_{s_1}^{\sigma(S)} \sum_{s_2 \neq s_1}^{\sigma(S)} \sum_{i}^{\sigma(C_{s_1})} \sum_{j}^{\sigma(C_{s_2})} I_{s_1 s_2}(i, j)$
$\mathcal{V}_d = \sum_{s}^{\sigma(S)} \sigma^2(C_{s_c})$	$\mathcal{V}_o = \sum_{s_1}^{\sigma(S)} \sum_{s_2 \neq s_1}^{\sigma(S)} \sigma(C_{s_1}) \sigma(C_{s_2})$

the outputs of one subsystem become the inputs of another. The couplings appear as the off-block diagonal of the DSM. The presence of centralized controllers greatly complicates the reconfiguration scenario. Process and resource boundaries are no longer equivalent and instead of a single interface for a given reconfiguration, there the three shown in Figure 5(b).

The corresponding DSM is shown on the left in Figure 10 and each type of interface is labelled with its corresponding region in the DSM. The Type I and II interfaces, as expected, appear on the off-block diagonal and therefore negatively affect the modularity measure. The Type III interfaces, however, appear within the block of the secondary resource and as a result positively affect the modularity measure. This is contrary to the previously developed intuition and raises doubts about the modularity measure as proposed.

To overcome this problem, the concept of “degree of freedom [7]based” modularity is proposed as an alternative to a “conventional” modularity. Instead of considering a module as a subsystem, a module is considered as the set of resources/components required to realize one or more complete production processes. The resulting DSM is shown on the right in Figure 10. This concept of a module is similar to the one used in Axiomatic Design. Suh writes: “A module is not a piece of hardware, although in some cases, it may coincidentally correspond to a hardware piece ... a module is defined as the row of a matrix that yields a functional requirement when it is provided with the input of its corresponding design parameter.” [74]

The degree of freedom-based DSM can be calculated using row and column swap operators. Specifically, the operator $U_{s_1 s_2}$ inserts column s_2 immediately after column s_1 and is explicitly defined as:

$$U_{s_1 s_2} = \begin{bmatrix} \lambda_1 & \cdots & \lambda_{s_1-1} & \lambda_{s_1} & \lambda_{s_2} & \lambda_{s_1+1} & \cdots & \lambda_{s_2-1} & \cdots \end{bmatrix} \quad (9)$$

where $s_1 < s_2$, e_i is the i^{th} elementary column vector, and $n = \sum_{s}^{\sigma(S)} \sigma(C_{s_c})$. Provided that $s_{1i} < s_{1i+1}$ and $s_{2i} < s_{2i+1}$, successive column swap operators can be used to move each

	Resource 1	Resource 2	Controller
Resource/Process 1		I	II
Resource/Process 2	I		II
Controller Process 1	II	II	
Controller Process 2	II	II	

(a) Conventional DSM

	Resource 1		Resource 2	
Resource/Process 1		II	I	II
Controller Process 1	II II		II II	III
Resource/Process 2	I	II		II
Controller Process 2	II II	III	II II	

(b) DOF-Based DSM

Figure 10. Design Structure Matrix of Two Primary & One Secondary Resource

centralized controller component to its associated degree of freedom.

$$\bar{I} = \left[\prod_i U_{\varsigma_{1_i} \varsigma_{2_i}} \right]^T I \left[\prod_i U_{\varsigma_{1_i} \varsigma_{2_i}} \right] \quad (10)$$

The degree of freedom based DSM includes Type III interfaces in its off-block diagonal. However, as shown in Figure 10, Equation 9 yields Type II interfaces that are now intra-modular and would not count correctly as part of the existing modularity measure. To compensate for this a combination of the two matrices can ensure that all three interface types are included correctly into a modularity measure. This modularity measure uses the same functional form as in Equation 8 but uses the variable expansion in Table III. This expansion adds the Type II interfaces to the a_o term and subtracts them from the a_d using an aggregation matrix which is defined as:

$$A(\kappa, \varsigma_1) = \begin{cases} 1 & \text{controller } q_\kappa \text{ controls subsystem } s_{\varsigma_1} \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

It is important to note that the DOF based measure always yields less modular values.

IV. ILLUSTRATIVE EXAMPLE

To demonstrate the application of the manufacturing measures, the hypothetical ‘‘Starling’’ automated manufacturing system is taken as an illustrative example. This system produces customized bird-feeders from cylindrical wooden components which need to be turned for slots and tabs, milled, assembled, and painted in one of three colors. They are transported between value adding resources and two independent buffers on three shuttles. The value-adding machines had their respective execution controllers, but also used a line-wide controller to schedule the parts to each of the machines. The shuttles, however, used a distributed approach so that each had its own ‘‘intelligent’’ software to schedule its activities. The initial configuration of the plant is shown in Figure 11(a) while Figure 11(b) shows it after the addition of a second turning station.

The calculation of manufacturing modularity in both phases can be realized in order to understand the facility with which new resources may be added to the system as it grows over time. If the Phase II system, for example, has a reduced modularity value, then this would suggest that as the system grows it is becoming increasingly less reconfigurable. The calculation of modularity is highly information intensive and much effort has to be expended initially to construct the production DSM. The component sets described in Section II-C are used in conjunction with a production DSM method [6], [7] to construct the DSM in Figure 12(a). Finally, the conversion from a conventional DSM to a DOF-based one is completed using Equation 9. These steps can be completed for each stage of the manufacturing system’s life and Figure 12 shows the two types of DSM for Stage I. At first, appearance the two matrices look the same. A closer look, however, shows that the machine scheduler subsystem has been removed from the conventional DSM. The interactions associated with its columns and rows have been added to the rows and

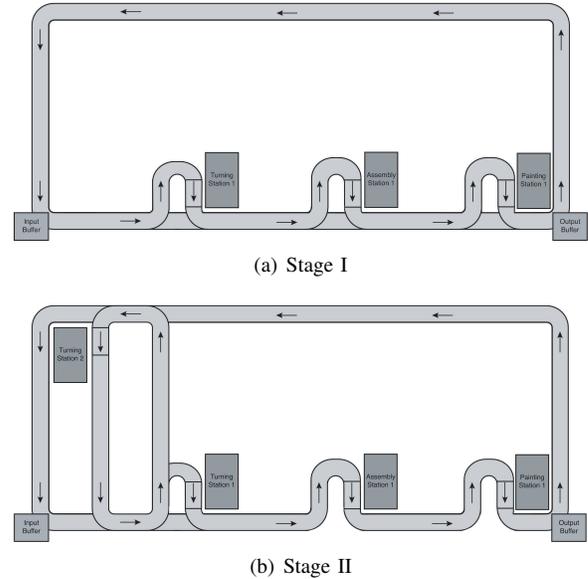


Figure 11. Starling Manufacturing System

columns of the value-adding machines. Most interestingly, this transformation has caused the value-adding machines to become directly coupled where there was no coupling before.

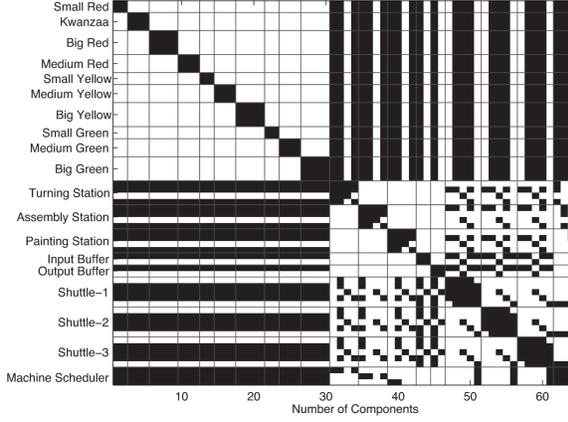
Table IV
MODULARITY MEASURES OF STARLING MANUFACTURING SYSTEM

	Stage I	Stage II
Modularity	0.5393	0.5319
DOF Modularity	0.4449	0.4166

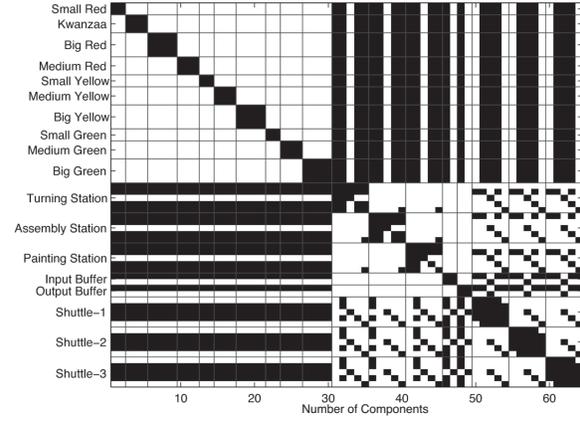
Once the production design structure matrix has been constructed, the modularity measures may be used to predict how easily a new resource may be introduced into the system. Table IV shows that prior to reconfiguration the conventional measure shows a moderate level (0.5393) of modularity. However, the DOF-based value (0.4449) highlights that the conventional measure may be over-estimated because the Type III interfaces within the machine scheduler need to be discounted from the modularity performance. In Stage II, after the new resource has been added, this disparity between the two types of modularity measures grows. The conventional measure (0.5319) remains relatively constant as one should not expect that the introduction of an additional machine would dramatically change the average density of the block and off-block diagonals. The degree of freedom based measure, however, decreases significantly (0.4166). The primary cause can be attributed to the growing role of Type III interfaces that appear when more machines controlled by the machine scheduler are added. One may expect that the two modularity values will continue to diverge as the number of centrally controlled resources grows and the associated coordination problem becomes increasingly complex. In conclusion, the two measures actually describe different aspects of the system. While the conventional measure describes how easily various modules may be pulled apart or put together, the DOF-based measure describes how easily the functions of a given resource

Table III
DEGREE OF FREEDOM EXPANSION OF MODULARITY VARIABLES

$a_d = \sum_{s_1} \sigma(\bar{S})$	$\sum_i \sigma(C_{s_{s_1}}) \sigma(C_{s_{s_2}}) \bar{I}_{s_1 s_2}(i, j) - \sum_{\kappa} A(\kappa, s_1) \sum_i \sigma(C_{s_{s_1}}) \sigma(C_{r_{\kappa}}) [I_{s_1 \kappa} + I_{\kappa s_1}](i, j)$	$\mathcal{V}_d = \sum_{s_1} \sigma^2(C_{s_{s_1}})$
$a_o = \sum_{s_1} \sigma(\bar{S})$	$\sum_{s_2 \neq s_1} \sigma(\bar{S}) \sigma(C_{s_{s_1}}) \sigma(C_{s_{s_2}}) \bar{I}_{s_1 s_2}(i, j) + \sum_{\kappa} A(\kappa, s_1) \sum_i \sigma(C_{s_{s_1}}) \sigma(C_{r_{\kappa}}) [I_{s_1 \kappa} + I_{\kappa s_1}](i, j)$	$\mathcal{V}_o = \sum_{s_1} \sigma(\bar{S}) \sum_{s_2 \neq s_1} \sigma(C_{s_{s_1}}) \sigma(C_{s_{s_2}})$



(a) Conventional DSM



(b) DOF-Based DSM

Figure 12. Design Structure Matrices of Starling Manufacturing System

may be integrated into the system as a whole.

These results suggest that in order to achieve an improved modularity value, one should act to minimize the information passed in order to achieve the system's required coordination activities. The details of this design process would ultimately require the system's modules to be decomposed to a finer level of detail such that individual information interface parameters/messages appear. As the designer makes these design decisions, the results would appear as increasingly sparse off-block diagonal and increasingly dense block diagonal. The implications of this statement are many. First of all, it indicates that systems should coordinate their activities with a minimum of information. Second, this statement gives initial quantitative support to many distributed manufacturing system design approaches that specifically try to minimize the number of messages passed between physical agents. Ideally, adopting such techniques would result in a relatively constant modularity value as the size of the systems grows with each reconfiguration.

V. CONCLUSIONS & FUTURE WORK

In the last three sections, two variants of manufacturing modularity were developed as measures of reconfiguration ease. First, interface complexity was argued to strongly affect modularity. Next, the literature was analyzed to develop a qualitative understanding of modularity. Finally, the manufacturing modularity measures were synthesized from this understanding of modularity and manufacturing interfaces.

Both modularity measures provide a quantitative description of *how many* interface parameters there are between

production subsystems. Meanwhile, any of the desired set of reconfigurations would necessarily have to pull apart and put back together these interfaces. The ease of this process would depend on how few interface parameters needed to be changed. Mathematically, the number of interface parameters changed is given by:

$$\sum_{s_1} \sigma(\bar{S}) \sum_{s_2} \sigma(\bar{S}) \sum_i \sigma(C_{s_{s_1}}) \sigma(C_{s_{s_2}}) \Delta I_{s_1 s_2}(i, j) \quad (12)$$

where $\Delta I_{s_1 s_2}(i, j)$ is the bitwise comparison of the initial and final design structure matrices I and \bar{I} respectively: $\Delta I_{s_1 s_2}(i, j)$

$$= \begin{cases} 0 & \text{if } s_1 = s_2 \\ I_{s_1 s_2}(i, j) & \text{if } s_1 \neq s_2 \text{ and } \bar{I}_{s_1 s_2}(i, j) \text{ does not exist} \\ \bar{I}_{s_1 s_2}(i, j) & \text{if } s_1 \neq s_2 \text{ and } I_{s_1 s_2}(i, j) \text{ does not exist} \\ |I_{s_1 s_2}(i, j) - \bar{I}_{s_1 s_2}(i, j)| & \text{otherwise} \end{cases} \quad (13)$$

The first condition corresponds to intra-subsystem interaction and hence affect configuration rather than reconfiguration activities. The next two conditions refer to reconfigurations that change the total number of subsystems and the corresponding interfaces that have to be pulled apart or put together. The final condition refers to a reconfiguration that holds constant the number of subsystems. The number of interface parameters corresponds negatively to both the reconfiguration ease measure $1 - (a_o/\mathcal{V}_o)$ and the modularity measure $(a_d/\mathcal{V}_d) - (a_o/\mathcal{V}_o)$.

Finally, this development of manufacturing modularity is the second of two papers in this issue that propose elements

of an integrated reconfigurability measurement process based upon the principles of reconfiguration potential [5], [7]–[9] and reconfiguration ease [3], [4], [6], [7], [32]. Future work seeks to unite these complementary principles in the context of case studies at the conceptual, laboratory and industrial scales [7]. More formalized research to develop methodologies for realizing the measurement process are ongoing [6], [76], [77].

REFERENCES

- [1] Y. Koren, U. Heisel, F. Jovane, T. Moriwaki, G. Pritschow, G. Ulsoy, and H. Van Brussel, "Reconfigurable manufacturing systems," *CIRP Annals - Manufacturing Technology*, vol. 48, no. 2, pp. 527–540, 1999.
- [2] M. Mehrabi, A. Ulsoy, and Y. Koren, "Reconfigurable manufacturing systems and their enabling technologies," *International Journal of Manufacturing Technology and Management*, vol. 1, no. 1, pp. 113–130, 2000.
- [3] A. Farid and D. McFarlane, "A tool for assessing reconfigurability of distributed manufacturing systems," in *INCOM 2006: 12th IFAC Symposium on Information Control Problems in Manufacturing*, Saint-Etienne, France, 2006.
- [4] —, "An approach to the application of the design structure matrix for assessing reconfigurability of distributed manufacturing systems," in *IEEE 2006 Workshop on Distributed Intelligent Systems Collective Intelligence and its Applications*, Prague, Czech Republic, 2006.
- [5] —, "A development of degrees of freedom for manufacturing systems," in *IMS'2006: 5th International Symposium on Intelligent Manufacturing Systems: Agents and Virtual Worlds*, Sakarya, Turkey, 2006.
- [6] —, "A design structure matrix based method for reconfigurability measurement of distributed manufacturing systems," *International Journal of Intelligent Control and Systems*, vol. Special Issue, 2007.
- [7] A. Farid, "Reconfigurability measurement in automated manufacturing systems," Ph.D. dissertation, University of Cambridge: Institute for Manufacturing, 2007.
- [8] —, "Production degrees of freedom as reconfiguration potential measures," (to appear in) *Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture*, 2008.
- [9] —, "Product degrees of freedom as reconfiguration potential measures," (to appear in) *ITSSA: International Transaction of Systems Science and Applications*, 2008.
- [10] S. Goldman, R. Nagel, and K. Preiss, *Agile Competitors and Virtual Organisations*. Van Nostrand Reinhold, 1995.
- [11] J. Pine, *Mass Customization: The New Frontier in Business Competition*. Boston, MA: Harvard Business School Press, 1993.
- [12] A. I. Dashchenko, *Reconfigurable Manufacturing Systems and Transformable Factories*. Springer, 2006.
- [13] R. Setchi and N. Lagos, "Reconfigurability and reconfigurable manufacturing systems – state of the art review," in *Innovative Production Machines and Systems: Production Automation and Control State of the Art Review*. Cardiff, United Kingdom: Innovative Production Machines and Systems: Network of Excellence, 2005, ch. 5, pp. 131–143.
- [14] R. G. Landers, B. K. Min, and Y. Koren, "Reconfigurable machine tools," *CIRP Annals - Manufacturing Technology*, vol. 50, pp. 269–274, 2001.
- [15] R. Brennan and D. Norrie, "Agents, holons and function blocks: Distributed intelligent control in manufacturing," *Journal of Applied Systems Science: Special Issue*, vol. 2, no. 1, pp. 1–19, 2001.
- [16] V. Vyatkin, *IEC 61499 Function Blocks for Embedded and Distributed Control Systems*, 2006.
- [17] W. Shen and D. Norrie, "agent-based systems for intelligent manufacturing: A state-of-the-art survey," *Knowledge and Information Systems: An International Journal*, vol. 1, no. 2, pp. 129–156, 1999.
- [18] W. Shen, D. Norrie, and J. Barthes, *MultiAgent Systems for Concurrent Intelligent Design and Manufacturing*. Taylor and Francis, 2000.
- [19] R. F. Babiceanu and F. F. Chen, "Development and applications of holonic manufacturing systems: A survey," *Journal of Intelligent Manufacturing*, vol. 17, pp. 111–131, 2006.
- [20] V. Marik, M. Fletcher, M. Pechoucek, O. Stepankova, H. Krautwurmova, and M. Luck, "Holons and agents: Recent developments and mutual impacts," in *Multi-Agent Systems and Applications II: Lecture Notes in Artificial Intelligence*. Springer Verlag, 2002, pp. 233–267.
- [21] D. McFarlane and S. Bussmann, "Holonic manufacturing control: Rationales, developments and open issues," in *Agent-Based Manufacturing*, S. Deen, Ed. Berlin: Springer-Verlag, 2003, ch. 13, pp. 303–326.
- [22] R. Brennan and D. Norrie, "Metrics for evaluating distributed manufacturing control systems," *Computers in Industry*, vol. 51, no. 2, pp. 225–235, 2003.
- [23] S. Bussmann and J. Sieverding, "Holonic control of an engine assembly plant an industrial evaluation," in *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, vol. 5, Tucson, AZ, 2001, pp. 3151–3156.
- [24] J.-L. Chirn, "Developing a reconfigurable manufacturing control system – a holonic component based approach." Ph.D. dissertation, University of Cambridge, 2001.
- [25] P. Leitao, "An agile and adaptive holonic architecture for manufacturing control," Ph.D. dissertation, University of Porto: Faculty of Engineering, 2004.
- [26] R. Beach, A. Muhlemann, D. Price, A. Paterson, and J. Sharp, "A review of manufacturing flexibility," *European Journal of Operational Research*, vol. 122, pp. 41–57, 2000.
- [27] R. Brennan, "Towards the assessment of holonic manufacturing systems," in *INCOM 2006: 12th IFAC Symposium on Information Control Problems in Manufacturing*, 2006.
- [28] Chirn and D. McFarlane, "Proceedings of the 16th ifac world conference," 2005.
- [29] A. De Toni and S. Tonchia, "Manufacturing flexibility: a literature review," *International Journal of Production Research*, vol. 36, no. 6, pp. 1587–1617, 1998.
- [30] H. A. ElMaraghy, "Flexible and reconfigurable manufacturing systems paradigms," *International Journal of Flexible Manufacturing Systems*, vol. 17, pp. 261–276, 2005.
- [31] R. V. Ramasesh and M. D. Jayakumar, "Measurement of manufacturing flexibility: A value based approach," *Journal of Operations Management*, vol. 10, pp. 446–468, 1991. [Online]. Available: <http://www.sciencedirect.com/science/article/B6VB7-45K1NHW-33/2/728722d9263ddaa406e7216fd4642097>
- [32] A. Farid, "A review of holonic manufacturing systems literature," University of Cambridge Institute for Manufacturing, Cambridge UK, Tech. Rep., 2004.
- [33] ANSI-ISA, "Enterprise control system integration part 3: Activity models of manufacturing operations management," ISA, Research Triangle Park, North Carolina, Tech. Rep., 2005.
- [34] R. Cerni and L. Foster, *Instrumentation for Engineering Measurement*. New York: John Wiley and Sons, 1962.
- [35] E. Dijkstra, "Beyond structured programming: An introduction to the principles of software metrics," *Journal of Structured Programming*, vol. 11, no. 1, 1990.
- [36] L. Ejiogu, *Software Engineering with Formal Metrics*. Boston: QED Technical Publishing Group: McGraw-Hill Book Company, 1991.
- [37] S. Eppinger, "The design structure matrix - dsm," <http://www.dsmweb.org/>, Tech. Rep., 2005.
- [38] M. Sosa, S. Eppinger, and C. Rowles, "Identifying modular and integrative systems and their impact on design team interactions," *Journal of Mechanical Design, Transactions of the ASME*, vol. 125, no. 2, pp. 240–252, 2003.
- [39] T. Pimmler and S. Eppinger, "Integration analysis of product decompositions," in *American Society of Mechanical Engineers, Design Engineering Division (Publication) DE*, vol. 68, Minneapolis, MN, USA, 1994, pp. 343–351.
- [40] Y. Zhang, J. Gershenson, and S. Allamneni, "Determining relationships between modularity and cost in product retirement," in *Proceedings of the ASME Design Engineering Technical Conference*, vol. 4, Pittsburgh, PA, United States, 2001, pp. 49–61.
- [41] D. Steward, "Design structure system: A method for managing the design of complex systems," *IEEE Transactions on Engineering Management*, vol. EM-28, no. 3, pp. 71–74, 1981.
- [42] C. Huang and A. Kusiak, "Modularity in design of products and systems," *IEEE Transactions on Systems, Man, and Cybernetics Part A: Systems and Humans*, vol. 28, no. 1, pp. 66–77, 1998.
- [43] Z. Siddique and D. Rosen, "On the applicability of product variety design concepts to automotive platform commonality," in *Proceedings of DETC '98: 1998 ASME Design Engineering Technical Conferences*, Atlanta, Georgia, 1998, pp. 1–12.
- [44] P. Gu, H. Rao, and M. Tseng, "Systematic design of manufacturing systems based on axiomatic design approach," *CIRP Annals - Manufacturing Technology*, vol. 50, no. 1, pp. 299–304, 2001.
- [45] D. McFarlane, S. Sarma, J. Chirn, K. Ashton, and C. Wong, "Auto id systems and intelligent manufacturing control," *Engineering Applications of Artificial Intelligence*, vol. 16, no. 4, pp. 365–376, 2003.

- [46] J. Gershenson, G. Prasad, and Y. Zhang, "Product modularity: measures and design methods," *Journal of Engineering Design*, vol. 15, no. 1, pp. 33–51, 2004.
- [47] H. Zuse, *Software Complexity: Measures and Methods*, ser. Programming Complex Systems. Berlin: W. de Gruyter, 1991.
- [48] M. Mehrabi, A. Ulsoy, and Y. Koren, "Reconfigurable manufacturing systems: key to future manufacturing," *Journal of Intelligent Manufacturing*, vol. 11, no. 4, pp. 403–419, 2000.
- [49] J. Gershenson, G. Prasad, and S. Allamneni, "Modular product design: A life-cycle view," *Journal of Integrated Design and Process Science*, vol. 3, no. 4, pp. 13–26, 1999.
- [50] P. Gu, M. Hashemian, and S. Sosale, "Integrated modular design methodology for life-cycle engineering," *CIRP Annals - Manufacturing Technology*, vol. 46, no. 1, pp. 71–74, 1997.
- [51] S. Sosale, M. Hashemian, and P. Gu, "Product modularization for reuse and recycling," in *American Society of Mechanical Engineers, Design Engineering Division (Publication) DE*, vol. 94, Dallas, TX, USA, 1997, pp. 195–206.
- [52] E. Allen and T. Khoshgoftaar, "Measuring coupling and cohesion: An information-theory approach," *International Software Metrics Symposium, Proceedings*, pp. 119–127, 1999.
- [53] M. Ammann and R. Cameron, "Measuring program structure with inter-module metrics," 1994, pp. 139–144.
- [54] L. Briand, J. Daly, and J. Wust, "Unified framework for coupling measurement in object-oriented systems," *IEEE Transactions on Software Engineering*, vol. 25, no. 1, pp. 91–121, 1999.
- [55] D. Chen and M. Torngren, "A metrics system for quantifying operational coupling in embedded computer control systems," in *EMSOFT 2004 - Fourth ACM International Conference on Embedded Software*, Pisa, Italy, 2004, pp. 184–192.
- [56] S. Chidamber and C. Kemerer, "Metrics suite for object oriented design," *IEEE Transactions on Software Engineering*, vol. 20, no. 6, pp. 476–493, 1994.
- [57] A. Lakhota and J. Deprez, "Restructuring functions with low cohesion," 1999, pp. 36–46.
- [58] A. Offutt, M. Harrold, and P. Kolte, "Software metric system for module coupling," *Journal of Systems and Software*, vol. 20, no. 3, pp. 295–308, 1993.
- [59] S. Kumar and M. Chandrasekharan, "Grouping efficacy: a quantitative criterion for goodness of block diagonal forms of binary matrices in group technology," *International Journal of Production Research*, vol. 28, no. 2, pp. 233–243, 1990.
- [60] R. Sandbothe, "Two observations on the grouping efficacy measure for goodness of block diagonal forms," *International Journal of Production Research*, vol. 36, no. 11, pp. 3217–3222, 1998.
- [61] S. Coulter, M. McIntosh, B. Bras, and D. Rosen, "Identification of limiting factors for improving design modularity," in *1998 ASME Design Engineering Technical Conferences*, Atlanta, Georgia, 1998, pp. 1–12.
- [62] A. Kusiak and E. Szczerbicki, "Transformation from conceptual to embodiment design," *IIE Transactions (Institute of Industrial Engineers)*, vol. 25, no. 4, pp. 6–12, 1993.
- [63] E. Arisholm, D. Sjoberg, and M. Jorgensen, "Assessing the changeability of two object-oriented design alternatives - a controlled experiment," *Empirical Software Engineering*, vol. 6, no. 3, pp. 231–277, 2001.
- [64] P. Gu and S. Sosale, "Product modularization for life cycle engineering," *Robotics and Computer-Integrated Manufacturing*, vol. 15, no. 5, pp. 387–401, 1999.
- [65] P. Winston, *On To Java*, 2001.
- [66] G. Myers, *Software Reliability: Principles and Practices*. Wiley, 1976.
- [67] W. Stevens, G. Myers, and L. Constantine, "Structured design," *IBM Systems Journal*, vol. 13, no. 2, pp. 115–139, 1974.
- [68] K. Ulrich, "The role of product architecture in the manufacturing firm," *Research Policy*, vol. 24, no. 3, pp. 419–440, 1995.
- [69] E. Yourdon and L. Constantine, *Structured design : fundamentals of a discipline of computer program and systems design*. Englewood Cliffs: Prentice Hall, 1979.
- [70] N. Suh, *The Principles of Design*. New York: Oxford University Press, 1990.
- [71] —, "Design and operation of large systems," *Journal of Manufacturing Systems*, vol. 14, no. 3, p. 203, 1995.
- [72] —, "Design of systems," *CIRP Annals - Manufacturing Technology*, vol. 46, no. 1, pp. 75–80, 1997.
- [73] —, "Axiomatic design theory for systems," *Research in Engineering Design - Theory, Applications, and Concurrent Engineering*, vol. 10, no. 4, pp. 189–209, 1998.
- [74] —, *Axiomatic Design: Advances and Applications*. New York: Oxford University Press, 2001.
- [75] K. Ulrich and S. Eppinger, *Product Design and Development*. New York: McGraw-Hill, 1995.
- [76] W. Covanich, D. C. McFarlane, and A. Farid, "Guidelines for evaluating the ease of reconfiguration of manufacturing systems," in *submitted to INDIN 2008*, 2008.
- [77] W. Covanich, D. C. McFarlane, J. Brusey, and A. Farid, "Ready configuration of machines into an existing manufacturing system," *International Journal of Agile Manufacturing*, vol. 10, no. 2, pp. 5–18, 2007.