# AXIOMATIC DESIGN & DESIGN STRUCTURE MATRIX MEASURES FOR RECONFIGURABILITY & ITS KEY CHARACTERISTICS IN AUTOMATED MANUFACTURING SYSTEMS

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## ABSTRACT

In recent years, the fields of reconfigurable manufacturing systems, holonic manufacturing systems, and multi-agent systems have made technological advances to support the ready reconfiguration of automated manufacturing systems. While these technological advances have demonstrated robust operation and been qualitatively successful in achieving reconfigurability, limited effort has been devoted to the measurement of reconfigurability in the resultant systems. Hence, it is not clear 1.) to which degree these designs have achieved their intended level of reconfigurability 2.) which systems are indeed quantitatively more reconfigurable and 3.) how these designs may overcome their design limitations to achieve greater reconfigurability in subsequent design iterations. Recently, a reconfigurability measurement process based upon axiomatic design and the design structure matrix has been developed. This paper now builds upon these works to provide a set of composite reconfigurability measures. Among these are measures for its key characteristics of integrability, convertibility, and customization, which have driven the qualitative and intuitive design of these technological advances. These measures are then demonstrated on an illustrative example followed by a discussion of how they may be practically applied in large automated manufacturing systems.

**Keywords**: Reconfigurability, axiomatic design for large flexible systems, design structure matrix, reconfigurable manufacturing systems, multi-agent systems

## 1 INTRODUCTION

Manufacturing has became increasingly characterized by continually evolving and ever more competitive marketplaces. In order to stay competitive, manufacturing firms have had to respond with a high variety products of increasingly short product lifecycle[Mehrabi et al. 2002; Pine 1993]. One particularly pertinent problem is the need to quickly and incrementally adjust production capacity and capability. To fulfill the needs of enterprises with extensive automation, reconfigurable manufacturing systems have been proposed as a set of possible solutions[Mehrabi et al. 2000]. They are defined as:

**Definition 1.** Reconfigurable Manufacturing System[Koren et al. 1999]: "[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."

Over the last decade, many technologies and design approaches each with their respective scope have been developed to enable reconfigurability in manufacturing systems[Dashchenko 2006; Setchi & Lagos 2005]. This is a cyber-physical challenge requires the careful design of functions, components and their interfaces be they of a material, energetic or informatics nature. Some of this work includes modular machine tools [Heilala & Voho 2001; Landers et al. 2001; Shirinzadeh 2002] and distributed automation[Brennan & Norrie 2001; Vyatkin 2007; Lepuschitz et al. 2010]. Additionally, a wide set of IT-based paradigms such as Multi-Agent Systems[Shen & Norrie 1999; Shen et al. 2000; Leitao 2009; Leitao & Restivo 2006; Leitao et al. 2012; Ribeiro & Barata 2013], Holonic Manufacturing Systems[Babiceanu & Chen 2006; Marik et al. 2002; McFarlane & Bussmann 2000; McFarlane et al. 2003] have emerged. While these technoligical advances have demonstrated robust operation and been qualitatively successful in achieving reconfigurability, there has been comparatively little attention devoted to design methodologies of these reconfigurable manufacturing systems and so their ultimate industrial adoption remains limited[Marik & McFarlane 2005].

One major challenge in the development of a reconfigurable manufacturing system design methodology is the absence of a reconfigurability measurement process. Hence, it is not clear 1.) the degree to which previous designs have achieved their intended level of reconfigurability, 2.) which systems are indeed quantitatively more reconfigurable 3.) how these designs may overcome their inherent design limitations to achieve greater reconfigurability in subsequent design iterations. Recently such a measurement process has been developed upon the foundation of axiomatic design for large flexible systems and the design structure matrix. Collectively, these works show that a high degree of reconfigurability is achieved by fostering greater reconfiguration potential through axiomatic design as well as greater reconfiguration ease. This paper now integrates these prior works to provide measures for reconfigurability and its key characteristics of integrability, convertibility, and customization.

This paper follows a five part discussion. Section **2** provides the foundation to this work. It uses axiomatic design

for large flexible systems and the design structure matrix to provide measures of reconfiguration potential and ease respectively. Section **3** then demonstrates how these measures may be used to synthesize more complex measures that address reconfigurability and its key characteristics: integrability, convertibility, and customization[Mehrabi et al. 2000b]. Section **4** then applies these measures to an illustrative example. Section **5** concludes the work.

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[ANSI-ISA 2005]. For simplicity, productions systems are assumed to have physically allocated distributed automation and control. Production systems with centralized controllers have been previously addressed in [Farid 2008]. Furthermore, this paper defines reconfigurability as:

**Definition 2**. Reconfigurability[Farid & McFarlane 2007]: 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.

## 2 BACKGROUND: FOUNDATIONS OF RECONFIGURABILITY MEASUREMENT

The composite measures presented in the next section are built upon a reconfigurability measurement process based upon axiomatic design for large flexible systems and the design structure matrix. While a deep treatment of the reconfigurability measurement process is not feasible here, the interested reader is referred to the background references for the details of the mathematical developments in this work [Farid & McFarlane 2008; Farid 2008a; Farid 2013; Farid 2008b; Farid 2014a; Farid 2014b; Viswanath et al. 2013; Farid & Covanich 2008; Baca et al. 2013; Farid & McFarlane 2006; Farid & McFarlane 2007; Farid 2007]. Figure **1** shows a conceptual representation of a reconfiguration process.
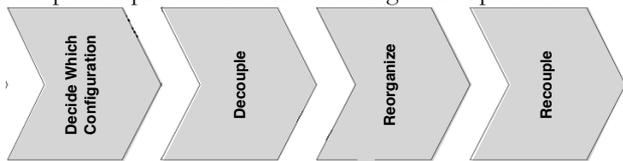


**Figure 1. A Four Step Reconfiguration Process**

Facilitating the potential for such a process can be achieved through axiomatic design while fostering reconfiguration ease can be achieved through the design structure matrix. The former is linked to the number of possible configurations of the system in a measure called production degrees of freedom. The latter is linked to the effort required to pull apart and reconnect interfaces in a measure of modularity. This section introduces the concept of a reconfigurability measurement process and then presents a set of definitions and measures for use in the following section.

## 2.1 MEASURABLES & MEASUREMENT METHODS

As shown in Figure **2**, the measurement of reconfigurability is naturally an indirect measurement process[Cerni & Foster 1962]. It requires that measurables be directly measured with measurement methods and then placed into models from which formulaic measures can give the desired measurement property of reconfigurability. In this work, the measurables are the production system's processes, resources, and their interfaces. These may be counted manually once the measurer has determined a consistent ontological basis for defining them[Gasevic et al. 2009]. However, with the advent of model-based systems engineering, this work instead assumes that there exists a virtual model of the production system and its control implemented in a language such as SysML[Friedenthal et al. 2011]. In such a case, the measurables of production processes, resources, and interfaces can be automatically extracted.



**Figure 2. A Generic Indirect Measurement Process**

## 2.2 AXIOMATIC DESIGN MEASURES: PRODUCTION DEGREES OF FREEDOM

Suh [2001] defines large flexible systems as systems with many functional requirements that not only evolve over time, but also can be fulfilled by one or more design parameters. In production systems, the high level design parameters are taken as the set of production resources. **DP**={Production Resources}. These resources $R = M \cup B \cup H$ may be classified into value adding machines $M = \{m_1 \ldots m_{\sigma(M)}\}$, independent buffers $B = \{b_1 \ldots b_{\sigma(B)}\}$, and material handlers $H = \{h_1 \ldots h_{\sigma(H)}\}$ where $\sigma()$ gives the size of a set. The set of buffers $B_S = M \cup B$ is also introduced for later simplicity. Similarly, the high level functional requirements are taken as a set of production processes. **FR**={Production Processes}. These are formally classified into three varieties: transformation, transportation and holding processes and are defined as:

**Definition 3.** Transformation Process[Farid & McFarlane 2008]: A machine-independent, manufacturing technology-independent process $p_{\mu j} \in P_\mu = \{p_{\mu 1} \ldots p_{\mu \sigma(P_\mu)}\}$ that transforms raw material or work-in-progress to a more final form.

**Definition 4.** Transportation Process[Farid & McFarlane 2008]: A material-handler - independent process $p_{\eta u} \in P_\eta = \{p_{\eta 1} \ldots p_{\eta \sigma(P_\eta)}\}$ that transports raw material, work-in-progress, or final goods from buffer $b_{sy1}$ to $b_{sy2}$. There are $\sigma^2(B_S)$ such processes of which $\sigma(B_S)$ are "null" processes where no motion occurs. Furthermore, the convention of indices $u = \sigma(B_S)(y_1-1) + y_2$ is adopted.

**Definition 5.** Holding Process[Farid & McFarlane 2008]: A material-handler and end-effector-independent process $p_{\varphi g} \in P_\varphi = \{p_{\varphi 1} \ldots p_{\varphi \sigma(P_\varphi)}\}$ that holds raw material, work-in-progress, or final products during the transportation from one buffer to another.

These production processes and resources may be related through the use of the axiomatic design equation for large flexible systems[Suh 2001].

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

where $\odot$ is "matrix Boolean multiplication"[Farid & McFarlane 2008] and **J$_S$** is the production system knowledge base.

**Definition 6**. Production System Knowledge Base[Farid & McFarlane 2008]: A binary matrix $\mathbf{J_S}$ of size $\sigma(P)x\sigma(R)$ whose element $\mathbf{J_S}(w,v)\in\{0,1\}$ is equal to one when event $e_{wv}$ exists as a production process $p_w$ being executed by a resource $r_v$.

In other words, the production system knowledge base itself forms a bipartite graph which maps the set of production processes to production resources. $\mathbf{J_S}$ can then be reconstructed straightforwardly from smaller knowledge bases that individually address transformation, transportation, and holding processes. $P_\mu = J_M \odot M$, $P_\mu = J_H \odot R$, $P_\gamma = J_\gamma \odot R$. $\mathbf{J_S}$ then becomes[Farid & McFarlane 2008]

$$J_S = \begin{bmatrix} J_M & | & \mathbf{0} \\ & J_{\bar{H}} & \end{bmatrix} \quad (2)$$

where in order to account for the simultaneity of holding and transportation processes[Farid 2013]

$$J_{\bar{H}} = \left[ J_\gamma \otimes \mathbf{1}^{\sigma(P_\eta)} \right] \cdot \left[ \mathbf{1}^{\sigma(P_\gamma)} \otimes J_H \right] \quad (3)$$

and $\otimes$ is the Kronecker product and $\mathbf{1}^n$ is a column ones vector length n.

In order to differentiate between the existence and the availability of a given production system capability, a production system scleronomic (i.e. sequence-independent) constraints matrix is introduced.

**Definition 7**. Production System Scleronomic Constraints Matrix[Farid & McFarlane 2008]: A binary matrix $K_S$ of size $\sigma(P)x\sigma(R)$ whose element $K_S(w,v) \in \{0,1\}$ is equal to one when a constraint eliminates event $e_{wv}$ from the event set.

It is calculated analogously to the production system knowledge base:

$$K_S = \begin{bmatrix} K_M & | & \mathbf{1} \\ & K_{\bar{H}} & \end{bmatrix} \quad (4)$$

where

$$K_{\bar{H}} = \left[ K_\gamma \otimes \mathbf{1}^{\sigma(P_\eta)} \right] \cdot \left[ \mathbf{1}^{\sigma(P_\gamma)} \otimes K_H \right] \quad (5)$$

From these definitions of $\mathbf{J_S}$ and $\mathbf{K_S}$, follows the definition of sequence-independent production degrees of freedom.

**Definition 8**. Sequence-Independent Production Degrees of Freedom[Farid & McFarlane 2008]: The set of independent production events $E_S$ that completely defines the available production processes in a production system. Their number is given by:

$$DOF_S = \sigma(E_S) = \sum_w^{\sigma(P)} \sum_v^{\sigma(R)} \left[ J_S \ominus K_S \right](w,v) \quad (6)$$

where $A\ominus B$ is "Boolean subtraction" or equivalently $A \cdot \bar{B}$. Note that the Boolean "AND" is equivalent to the hadamard product and $\bar{B} = not(B)$.

In addition to these sequence-independent production degrees of freedom, it is necessary to introduce a measure for the sequence-dependent capabilities of the production system given that constraints often arise between two events [Farid & McFarlane 2008].

**Definition 9.** Sequence Dependent Production Degrees of Freedom[Farid & McFarlane 2008]: The set of independent production strings $z_{\varphi\psi}=e_{w1v1}e_{w2v2}\in \mathbf{Z}$ of length 2 that completely describe the production system language. Their number is given by:

$$DOF_\rho = \sigma(Z) = \sum_\varphi^{\sigma^2(P)} \sum_\psi^{\sigma^2(R)} \left[ J_\rho \ominus K_\rho \right](\varphi,\psi) \quad (7)$$

where $\mathbf{J_\rho}$ and $\mathbf{K_\rho}$ are defined below.

**Definition 10.** Rheonomic production system knowledge base[Farid & McFarlane 2008]: A binary matrix $\mathbf{J_\rho}$ of size $\sigma^2(P)x\sigma^2(R)$ whose element $J(\varphi,\psi)\in\{0,1\}$ are equal to one when string $z_{\varphi\psi}$ exists. It may be calculated directly as:

$$J_\rho = \left[ J_S \cdot \bar{K}_S \right] \otimes \left[ J_S \cdot \bar{K}_S \right] \quad (8)$$

This implies the index relations: $\varphi=\sigma(P)(w_1-1)+w_2$, and $\psi=\sigma(R)(v_1-1)+v_2$. The availability of these strings is reflected in an associated constraints matrix.

**Definition 11.** Rheonomic Production Constraints Matrix $K_\rho$[Farid & McFarlane 2008]: a binary constraints matrix of size $\sigma^2(P)x\sigma^2(R)$ whose elements $\mathbf{K_\rho}(\varphi,\psi)\in\{0,1\}$ are equal to one when string $z_{\varphi\psi}$ is eliminated.

In addition to the above, it is necessary to introduce the concept of product degrees of freedom as those production degrees of freedom applicable to a product line. A given enterprise may have a whole product line $L=\{l_1,...,l_{\sigma(L)}\}$. Each product $l_i$ has its associated set of product events $e_{xli} \in E_{li}$ which when all are completed result in a fully manufactured product.

**Definition 12.** Product Event[Farid & McFarlane 2008]: A specific transformation process that may be applied to a given product.

The relationship between product events and scleronomic transformation and transportation degrees of freedom is achieved with production feasibility matrices.

**Definition 13**. Product Transformation Feasibility Matrix $\Lambda_{\mu i}$ [Farid 2008]: A binary matrix of size $\sigma(E_{li})x\sigma(P_\mu)$ whose value $\Lambda_{\mu i}(x,j)=1$ if $e_{xli}$ realizes transformation process $p_{\mu j}$.

**Definition 14.** Product Transportation Feasibility Matrix $\Lambda_{\gamma i}$ [Farid 2008]: A binary row vector of size 1x $\sigma(P_\gamma)$ whose value $\Lambda_{\gamma i}=1$ if product $l_i$ can be held by holding process $p_{\gamma g}$.

From these definitions, it is straightforward to assess the number of product transformation and transportation degrees of freedom[Farid 2013].

$$DOF_{LM} = \langle \Lambda_{ML} \cdot J_M, \bar{K}_M \rangle_F \quad (9)$$

$$DOF_{LH} = \langle \Lambda_{HL} \cdot J_{\bar{H}}, \bar{K}_{\bar{H}} \rangle_F \quad (10)$$

where

$$\Lambda_{ML} = \overset{\sigma(L)}{\underset{i}{V}} \overset{\sigma(E_L)}{\underset{x}{V}} \Lambda_{\mu i}^T \mathbf{1}^{\sigma(M)T} \quad (11)$$

$$\Lambda_{HL} = \left[ \left( \overset{\sigma(L)}{\underset{i}{V}} \Lambda_{\gamma i} \right) \otimes \mathbf{1}^{\sigma(P_\eta)T} \right]^T \mathbf{1}^{\sigma(R)T} \quad (12)$$

The intuitive form of product degrees of freedom in Equations (9) and (10) shows that the product line effectively

selects out the production degrees of freedom provided by the production system. The former is ultimately a subset of the latter as a product naturally restricts the scope of a production system[Farid 2008].

This subsection has used axiomatic design for large flexible systems to produce production degree of freedom measures that represent the reconfiguration potential of a production system. The following subsection shifts its attention to reconfiguration ease.

## 2.3 DESIGN STRUCTURE MATRIX MEASURE: MODULARITY

In this subsection, modularity is addressed as one of the key characteristics of reconfigurable manufacturing systems. As shown in Figure **3**, the decoupling and coupling of products and resources must be considered not just physically but at all of the ISA-S95 control levels.
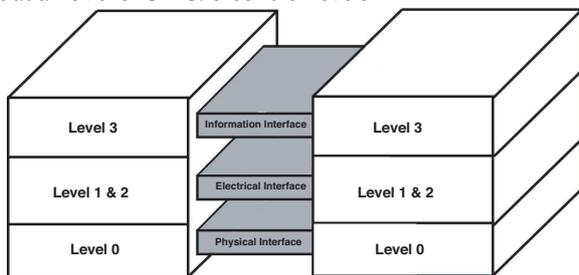


**Figure 3. Conceptual Representation of Multi-Level Interfaces of Production Resources & Products**

Here, the production design structure matrix[Farid 2008] is used to produce a modularity measure to suitably represent reconfiguration ease. It has a block form for all of the production system entities including products, buffers, material handlers, and value-adding machines. It is shown in Figure **4**. The associated measure of modularity is given by

$$\Gamma = \left[\frac{a_d}{V_d}\right] - \left[\frac{a_o}{V_o}\right] \qquad (13)$$

where $a_d$ is the total cohesion defined as the sum of all of the elements along the block diagonal, $a_o$ is the total coupling defined as the sum of all of the elements outside the block diagonal, $V_d$ is the total possible cohesive interaction defined as the number of elements in the block diagonal, $V_o$ is the total possible coupling interaction defined as the number of elements outside the block diagonal[Farid 2008]. From this foundation, the discussion can turn to the introduction of the composite reconfigurability measures.



**Figure 4. Production Design Structure Matrix**

# 3 COMPLEX RECONFIGURABILITY MEASURES

The previous section summarized two sets of reconfigurability measures: one for reconfiguration potential and another for reconfiguration ease. This section now demonstrates how these measures may be used to synthesize more complex measures that address reconfigurability and its remaining key characteristics: integrability, convertibility, and customization[Mehrabi et al. 2000b]. Each of these is now discussed in turn.

## 3.1 INTEGRABILITY

As the second of four key reconfigurability characteristics, it has been described as[Mehrabi et al. 2000b]:
**Integrability**: The ability with which systems and components may be readily integrated and future technology introduced.
In the context of this work, this description is interpreted as the ability to add or remove resources.

As shown in Figure **1**, such a reconfiguration requires two resources to be first determined and then subsequently pulled apart or put together. Rheonomic production degrees of freedom quantifies the first step with a mathematical description of the resource and their associated capabilities. The effort required for the second step can be quantified using the modularity of the pair of resources. Then, the pair of resources must be considered as their own system with a design structure matrix composed of four blocks from the larger DSM. Finally, to eliminate the effect of cohesion on reconfiguration ease, the cohesion term is replaced with unity. The resulting measure of integrability is:

$$I = \sum_{\psi}^{\sigma^2(R)}\left[1 - \frac{a_{o\psi}}{V_{o\psi}}\right]\sum_{\varphi}^{\sigma^2(P)}[J_\rho \ominus K_\rho](\varphi,\psi) \qquad (14)$$

This equation shows that the integrability of a system is measured in terms of the effort saved to integrate the rheonomic production degrees of freedom of a pair of resources summed overall resource pairs. Seen a different way, each degree of freedom is discounted by the amount of effort required to integrate it into the rest of the system. The system integrability can be normalized by its maximal value which it reaches in the absence of rheonomic constraints and inter-resource coupling.

## 3.2 CONVERTIBILITY

The convertibility of a manufacturing system can be addressed similarly. It is described as[Mehrabi et al. 2000b]:
**Convertibility**: The ability of the system to quickly changeover between existing products and adapt to future products.

This description, within the scope of the desired reconfigurations, can be interpreted as the ability to add or remove products from the product line. Such a reconfiguration requires that a product and resource be chosen and then be pulled apart or put together. Scleronomic product degrees of freedom quantifies the first step with the resource-product feasibility. To do this, one must recall that the relationship between product and transportation and transformation degrees of freedom is fundamentally different.

As a result, two convertibility measures are developed. The effort required for the second step can be quantified using the modularity of the resource-product pair. The resulting convertibility measures are:

$$C_M = \sum_i^{\sigma(L)} \sum_j^{\sigma(P_\mu)} \sum_k^{\sigma(M)} \left[1 - \frac{a_{oik}}{V_{oik}}\right]\left[\Lambda_{Mi} \cdot J_M \cdot \bar{K}_M\right](j,k) \quad (15)$$

$$C_H = \sum_i^{\sigma(L)} \sum_\varrho^{\sigma(P_{\bar{\eta}})} \sum_v^{\sigma(R)} \left[1 - \frac{a_{oiv}}{V_{oiv}}\right]\left[\Lambda_{Hi} \cdot J_{\bar{H}} \cdot \bar{K}_{\bar{H}}\right](\varrho,v) \quad (16)$$

where

$$\Lambda_{Mi} = \left[\overset{\sigma(E_L)}{\underset{x}{V}} \Lambda_{\mu i}\right]^T \mathbf{1}^{\sigma(M)T} \quad (17)$$

$$\Lambda_{Hi} = \left[\Lambda_{\gamma i} \otimes \mathbf{1}^{\sigma(P_\eta)T}\right]^T \mathbf{1}^{\sigma(R)T} \quad (18)$$

These measures show that the convertibility of a system is measured in terms of the effort saved to integrate the scleronomic product degrees of freedom of a product-resource pair summed over all product-resource pairs. Much like integrability, each degree of freedom is discounted by the amount of effort required to integrate it into the rest of the system. The two convertibility measures can be normalized by their respective maximal values which it reaches in the absence of scleronomic constraints and product-resource coupling.

### 3.3 CUSTOMIZATION

In many ways, the characteristic of customization has already been addressed in terms of product degrees of freedom. It is described as[Mehrabi et al. 2000b]:

**Customization:** The degree to which the capability and flexibility of the manufacturing system hardware and control match the application (product family).

This description suggests that customization is a relative measure that compares scleronomic product degrees of freedom versus scleronomic production degrees of freedom. A customization measure may be formulated as:

$$C = \frac{DOF_{LM} + DOF_{LH}}{DOF_S} \quad (19)$$

Such a measure over zero to one clearly expresses how many of the manufacturing system's capabilities are being used by the existing production line. In such a way, it may be used to rationalize either the expansion of the product line, or the removal of excess capabilities.

### 3.4 RECONFIGURABIITY

Given the measures for the four the key characteristics of modularity, integrability, convertibility and customization, a measure for reconfigurability can be synthesized. Within this work, reconfigurability is defined as in the introduction and the desired set of alternate configurations includes the addition and/or removal of products and resources. These two types of reconfigurations have already been addressed independently in terms of integrability and convertibility. Hence, a reconfigurability measure can be reasonably synthesized as the sum of the two characteristics.

$$R = I + C_M + C_H \quad (20)$$

This measure marks the completion of the reconfigurability measurement process on the dual foundation of axiomatic design for large flexible systems and the design structure matrix. The former gives a sense of productions systems' reconfiguration potential while the latter gives a sense of its reconfiguration ease.

## 4 ILLUSTRATIVE EXAMPLE: STARLING MANUFACTURING SYSTEM

To demonstrate the reconfigurability measure and its key characteristics, the "Starling Manufacturing System" is taken as a test case for its functional heterogeneity and redundancy, its resource flexibility, and its moderate size. The interested reader is referred to earlier references on reconfigurability measurement for fully worked examples on this test case[Farid 2007; Farid & McFarlane 2008; Farid & McFarlane 2006a; Farid & McFarlane 2007; Farid & Covanich 2008; Farid 2008a; Farid 2008b; Farid & McFarlane 2006b). Here, the essential aspects of the test case are included before presenting the associated quantitative results.
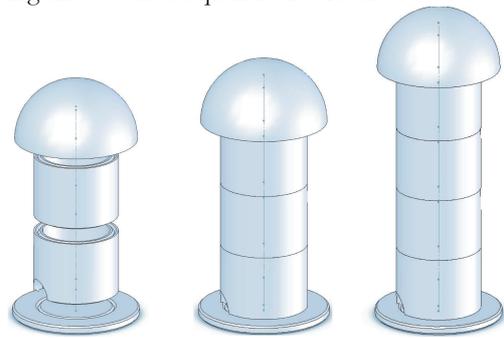
**Figure 5. CAD Model of Starling Bird Feeders**

The system produces customized bird feeders from cylindrical wooden components. The customer can choose between small, medium, and large bird-feeders which have two, three, or four cylinders respectively. Any of the product configurations can be offered in red, yellow or green. Thus, nine product types are regularly offered. Finally, all of the bird-feeders have an injection moulded dome roof and base which doubles as a bird perch. These two components are manually snapped onto the cylindrical birdfeeders after production and are not further discussed in this example. Figure **5** shows the four component parts and how they may be assembled into three possible configurations of the product line. In addition to this regular range of products, a seasonal "specialized product" from time to time is added. It is composed of independently painted red, yellow and green cylinders with large radii.
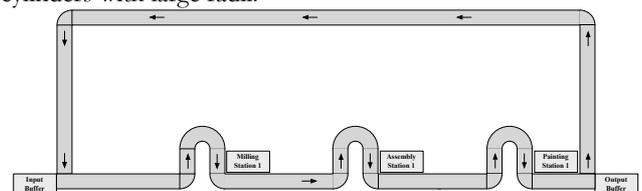
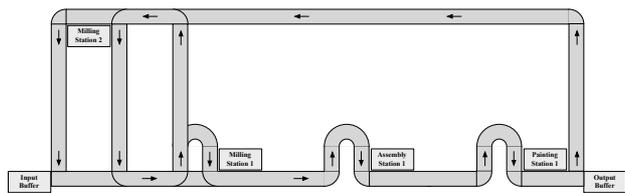**Figure 6. Phase I of Starling Manufacturing System**

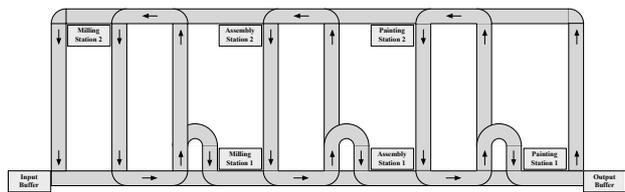**Figure 7. Phase II of Starling Manufacturing System**



**Figure 8. Phase III of Starling Manufacturing System**

These wooden cylinders are turned for slots and tabs, milled, assembled and painted. Two shuttles transport them between value adding resources and the two independent buffers. Figure **6** shows the initial configuration, Figure **7** adds a second machining station, and Figure **8** makes all three value-adding resources redundant.
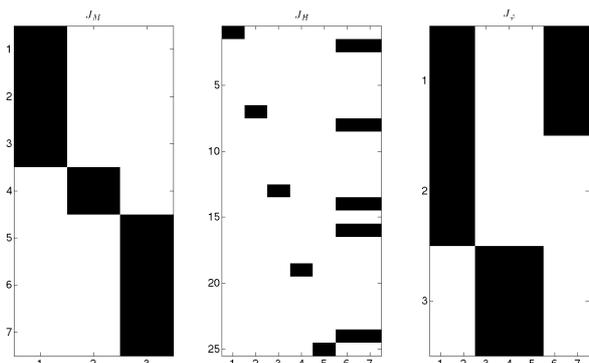


**Figure 9. Starling Manufacturing System Knowledge Base**

Next, the following sets of processes and resources are identified. In Phase I, M={Turning Station 1, Assembly Station 1, Painting Station 1}. B={Input Buffer, Output Buffer}. H={Shuttle A, Shuttle B}. $P_\mu$={Lathe Tab, Lathe Slot, Mill Hole, Assemble, Paint Red, Paint Yellow, Paint Green}. $P_\eta$ = {m\_im\_j, m\_ib\_k, b\_km\_i, b\_kb\_l} $\forall$ i,j=1,2,3, k,l=1,2. $P_\gamma$={Small Radial, Big Radial, Axial}. The production processes and resources for the other system configurations may be determined analogously. Figure **9** presents the transformation, transportation, and holding knowledge bases for the Starling Manufacturing System in Phase I as monochrome images. The scleronomic constraints matrices are initially set to zero. The rheonomic constraints matrix has the minimal constraints previously identified. The knowledge bases, constraints matrices, and product feasibility matrices for the other production system configurations and product variants can be readily formed by analogy. This example is fully worked in [Farid 2007; Farid & McFarlane 2008].

The production design structure matrix for Stage I is taken as given from the worked example in [Farid 2008] and is shown graphically in Figure **7**.

On this foundation, the numerical results for

reconfigurability and its key characteristics are summarized in Table **1**. Absolute measurements are shown plainly. Figures in parentheses are normalized to a comparable but ideal system with no sclemonic constraints, the minimal rheonomic constraints, and no coupling on the off-block diagonal of the production design structure matrix.
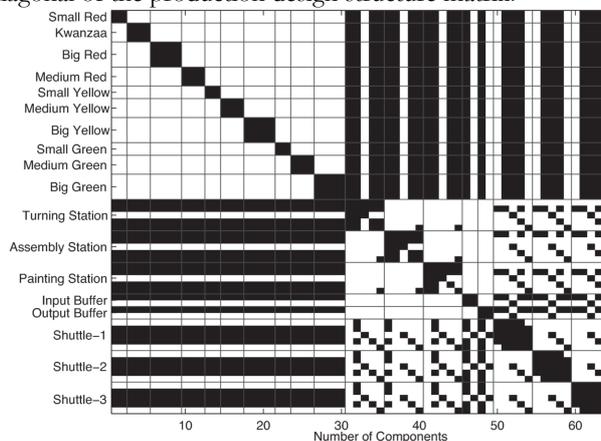


**Figure 10. Starling Manufacturing System Production Design Structure Matrix**

The values found in Table **1** shed some interesting insights into the Starling manufacturing system in both relative and absolute terms. Relatively speaking, the system is highly integrable. About 7/8 of the available rheonomic production degrees of freedom are achieved. The modest loss can be attributed to the required integration effort between material handlers and other resources. Rheonomic constraints are not part of the normalized figure because the normalization used the norm of a minimally constrained system. The convertibility values are substantially lower at approximately 1/5 and 2/5's respectively. This is to be expected because products and resources are typically much more coupled than resources are with each other. Finally, the system is fully customized because the product line makes use of all of the available production processes. These relative values are fairly constant over the three stages of the system's life. This result is also expected as the average number of integration interfaces per pair of subsystems is relatively constant over time. One would expect these values to vary if there were a massive refactoring of the system's overall structure.

**Table 1. Reconfigurability & its Key Characteristics for Starling Manufacturing System**

|  | Stage I | Stage II | Stage III |
|---|---|---|---|
| **Integrability** | 134.92 (0.8705) | 348.72 (0.8675) | 2475 (0.8980) |
| **Transformation Convertibility** | 10.4 (0.20) | 16.4 (0.20) | 20.8 (0.20) |
| **Transportation Convertibility** | 76 (0.38) | 150 (0.3846) | 538 (0.3927) |
| **Customization** | 1 | 1 | 1 |
| **Reconfigurability** | 221.32 (0.5438) | 515.12 (0.5894) | 3033.8 (0.7172) |

From an absolute measurement perspective, the most interesting trend is the relative sizes of the integrability and convertibility measures. Over the three stages, a number of resources were added and the associated rheonomic degrees of freedom grew substantially. At the same time, the size of the product line was held constant. As a result, the reconfigurability values became increasingly dominated by the integrability term rather than the convertibility terms. These results are consistent with the intuitive descriptions and are insightful. They encourage the use of the suite of measures rather than relying on the reconfigurability measure alone. Large relative reconfigurability measures could be caused by an exceptionally large number of loosely coupled capabilities, a well-leveraged and easily configured product line or both.

The demonstration of the key characteristic measures serves two fundamental purposes. First, as a group, they give a multi-faceted picture of the reconfigurability of a manufacturing system. The facility of adding products and resources is addressed and the degree to which the system is utilizing its capabilities is also represented. These measures also demonstrate the fundamental reliance on manufacturing modularity and degrees of freedom. The combination of manufacturing modularity with manufacturing degrees of freedom is also objective and consistent. Highly integrable and convertible systems should ideally have high numbers of degrees of freedom. These degrees of freedom should also be easily integrated into the remainder of the manufacturing system. In this way, one may conceive a number of practical questions for which the integrability and convertibility measures have direct application:

- How much more easily would a new resource be integrated into one plant versus another? (integrability)
- Which of two new resources would be more easily integrated into a single plant? (integrability)
- How much more easily would a new product be integrated into one plant versus another? (convertibility)
- How much more easily would a new resource allow the production of the existing production line? (convertibility)?

In such a way, production degrees of freedom and modularity make a convincing sufficiency case towards reconfigurability measurement.

From the perspective of practical application, the reconfigurability and key characteristic measures provided in this work are very much data intensive. Nevertheless, their underling axiomatic design for large flexible systems' knowledge base and the production design structure matrix are entirely compatible with model based systems engineering (MBSE) and their associated software tools. Therefore, it is very likely that these measures can be practically incorporated into such software tools as MBSE becomes the norm in production system design and control and automation system integration.

## 5 CONCLUSION

This work has built upon the recently developed reconfigurability measurement produce measures of reconfigurability and its key characteristics of modularity, integrability, convertibility, and customization as applied to reconfigurable manufacturing systems. To that end it used the axiomatic design for large flexible systems' knowledge base to address reconfiguration potential and the production design structure matrix to address reconfiguration ease. These measures represent the completion of the reconfigurability measurement process and have been applied on illustrative example consistent with previous work. In the future, the authors envision that these measures will be integrated into model based systems engineering tools that system integrators can use in the engineering design of production systems.

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