# *Measures of reconfigurability and its key characteristics in intelligent manufacturing systems*

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# Measures of reconfigurability and its key characteristics in intelligent 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 knowledge base and the design structure matrix has been developed. Together, they provide quantitative measures of reconfiguration potential and ease. This paper now builds upon these works to provide a set of composite reconfigurability measures. Among these are measures for the key characteristics of reconfigurability: 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 adhere to requirements for reconfigurability measurement in automated and intelligent manufacturing systems.

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## 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 of products of increasingly short product lifecycle (Mehrabi et al. 2002; Pine 1993). This mass-customization problem (Smith et al. 2013a, b; Kristianto et al. 2013). 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 and Lagos 2005). This is a cyber-physical challenge that requires the careful design of functions, components and their interfaces be they of a material, energetic or informatic nature. Some of this work includes modular machine tools and material handlers (Heilala and

Voho 2001; Landers et al. 2001; Shirinzadeh 2002; Müller et al. 2013) and distributed automation (Brennan and Norrie 2001; Vyatkin 2007; Lepuschitz et al. 2010; Vallee et al. 2011). Additionally, a wide set of artificially intelligent paradigms such as multi-agent systems (Shen and Norrie 1999; Shen et al. 2000; Leitao 2009; Leitao and Restivo 2006; Leitao et al. 2012; Ribeiro and Barata 2013; Lin et al. 2013; Trappey et al. 2013), and Holonic manufacturing systems (Babiceanu and Chen 2006; Marik et al. 2002; McFarlane and Bussmann 2000; McFarlane et al. 2003) have emerged. This work is particularly concerned with the integration of these intelligent control techniques within manufacturing systems. While these technological advances have demonstrated robust operation and been *qualitatively* successful in achieving reconfigurability, there has been comparatively little attention devoted to *quantitative* design methodologies of these reconfigurable manufacturing systems and so their ultimate industrial adoption remains limited (Marik and McFarlane 2005).

## Contribution

The contribution of this paper is a set of measures for reconfigurability and its key characteristics in intelligent manufacturing systems. In the past, one major challenge in the development of a reconfigurable manufacturing system design methodology is the absence of a *quantitative* 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, a measurement method has been developed to extract the necessary measurables from the production shop floor (Farid and McFarlane 2007). Once completed, basic measures of reconfiguration potential were developed upon the foundation of axiomatic design for large flexible systems (Farid and McFarlane 2008). Additionally, measures of reconfiguration ease were developed upon the foundation of the design strutter matrix (Farid 2008a). This paper, for the first time, builds upon these prior works and combines to quantify reconfigurability and its key characteristics of integrability, convertibility and customization.

## Paper outline

This paper follows a seven part discussion. The paper begins with a two-section background. The second section identifies a set of requirements for reconfigurability measurement in automated manufacturing systems. The third section recounts the existing fundamental measures of reconfiguration potential (Farid and McFarlane 2008) and ease (Farid 2008a) found within the literature. The fourth section, as the key contribution of this paper 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. 2000). The fifth section applies these measures to an illustrative example. The sixth section discusses the adherence of these newly developed measures to the requirements identified in "Reconfigurability measurement requirements in automated manufacturing systems" section. The seventh section concludes the work as a culmination of the reconfigurability measurement process for intelligent manufacturing systems.

## Scope

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) as shown in Fig. 1. This work is particularly interested in the reconfigurability of manufacturing system that have integrated distributed artificial intelligence as a class of systems. Therefore, the discussion is restricted to the manufacturing control system architecture depicted on the right hand side of Fig. 1. Note, that here the automation objects and intelligent agents match 1-to-1 with the physical production resources. It is this property that is later exploited in the reconfiguration potential measures recalled in "Reconfiguration potential measures: production degrees of freedom" section (Farid and McFarlane 2008; Farid 2008a). That said, a reader interested in the reconfiguration potential measurement of manufacturing

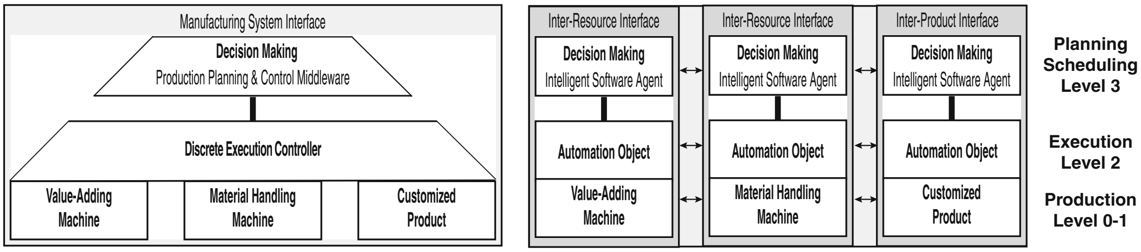


**Fig. 1** Conceptual representations of centralized versus intelligent distributed manufacturing systems (Farid 2007)

system in general is referred to previous work where centralized control system architectures are treated (Farid and McFarlane 2008; Farid 2008a).

Furthermore, this paper defines reconfigurability as:

**Definition 2** (*Reconfigurability* Farid and 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; chosen here to be the addition/removal of new products and resources.

## Reconfigurability measurement requirements in automated manufacturing systems

Prior to proceeding with the development of reconfigurability measures for automated manufacturing systems, a set of requirements for such measures must be identified. This section describes three categories of requirements: requirements for reconfigurability description, suitability requirements for manufacturing systems and finally requirements for measurement.

### Requirements for reconfigurability description

From Definition 2, four pieces of information are required to describe reconfigurability.

1. Definition of system and its boundary
2. Definition of system configuration
3. Description and rationale for a desired set of reconfigurations
4. Description of time/cost/effort of potential reconfigurations

First, any description of a reconfigurable system implicitly requires that the system and its boundary be fixed so as to define the domain of the measure function. While this may seem obvious, a reconfigurable system provides a unique challenge in that its definition may change over time. To overcome this, a reconfigurable system is analyzed over a time interval between two reconfiguration processes. Next, the system configuration must be described. From a systems engineering perspective, a system configuration is taken as equivalent to its system structure.

**Definition 3** (*System structure* Oliver et al. 1997) The parts of a system and the relationships amongst them. It is described in terms of:

- A list of all the components that comprise it
- What portion of the goal system behavior is carried out by each component
- How the components are interconnected

Therefore, the system configuration must be described in terms of its functions, components, and their interrelationships. Two types of relationships can be studied: function–component relationships and component–component relationships. The former describes the allocation of functionality to system components and hence gives a measure of its capabilities (Farid and McFarlane 2008). The latter describes the interfaces between components and hence gives a measure of interface complexity. Finally, to assure the timeliness and cost-effectiveness of potential reconfigurations, the reconfigurability measure would require some estimation of reconfiguration time, cost or effort.

### Suitability requirements for manufacturing systems

The special characteristics of a manufacturing system impose an additional set of heterogeneity requirements on the measurement process.

1. It must directly address the value-added machines, material handlers, and buffers as a heterogeneity of operating resources
2. It must directly address the system's transformation, transportation, and storage activities as a heterogeneity of functionality.
3. It must directly address product variants as a heterogeneity of operands.
4. It must describe processes that occur in many energy domains (e.g. mechanical, electrical, thermodynamic).
5. It must describes interactions of material, energy, information, and space.
6. It must be capable of addressing different types of control (real-time, execution, scheduling etc.)

In this regard, a tailored reconfigurability measure must necessarily address the transformation and transportation processes of a manufacturing system and the components/resources that realize them. These processes and their sequence may occur over multiple energy domains. Therefore, any models used must be rich enough to describe the diversity of mechanical, electrical, chemical and information processes. Similarly, interfaces may exchange material, energy and/or information. These models must also accommodate varying degrees of distribution/centralization. This is further complicated by the broad heterogeneity of manufacturing control and their associated technologies. A single manufacturing systems may use G-code for CNC, IEC61499 (Vyatkin 2007) for execution control, CORBA (Group 2007) as a system platform, and JADE-based software (Bellifemine et al. 2007) for planning and scheduling which all communicate over a combination of deterministic or stochastic

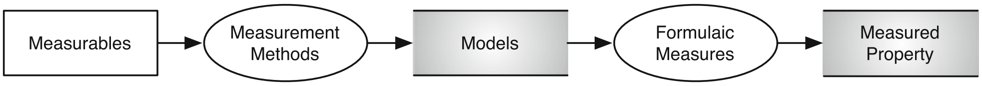


**Fig. 2** A generic indirect measurement process

networks. This heterogeneity requirement is further amplified when considering that reconfigurations occur on a time scale comparable with technology migration. Hence, over the life-cycle of a manufacturing facility, one can expect a wide variety of technologies that a reconfigurability measurement approach must address.

## Requirements for measurement

Measurement processes may be classified as either direct or indirect. As shown in Fig. 2, the latter is distinguished by the presence of models and formulaic measures (Cerni and Foster 1962). This results in five requirements which closely follow the steps in Fig. 2.

1. Identification of measurables
2. Methods for directly measuring the measurables
3. Standardizing space/model to describe system.
4. Formulaic measures of relating those models to desired properties
5. Identification of desired properties

At the beginning of the measurement process, the measurables are those which describe system structure: functions, components and their interrelationships. At the end, the set of measured properties are reconfigurability and its key characteristics. These two distinct sets must be related by one or more models. These models serve as an abstract standardizing space of the measurement much like the Euclidian line does for length measurement. As reconfigurability is a structural property, a physical modeling approach is most appropriate. A black box modeling approach would require the impractical approach of a statistically valid model developed after a large number of production system reconfigurations had been completed. Finally, the mathematical theory of measurement (Dijkstra 1990; Munroe 1971) requires a set of measures which relate the models to the desired properties. These must fulfill the requirements of a scale (Stevens 1946) and should have the following desirable qualities (Ejiogu 1991).

- Empirically and intuitively persuasive in relation to the standardizing space
- Simple and computable
- Consistent and objective
- Consistency of units and dimensions
- Feedback effect for design

A measure should quantitatively describe the intuitive notion of the given property. As a prerequisite, this requires a level of agreement in the intuition. More formally, the theory of measurement requires the fulfillment of two fundamental axioms independent of and prior to any numerical formulations:

**Axiom 1** (*Symmetry of preference* Zuse 1991) If one prefers $a_1 \in A$ to $a_2 \in A$, one does not prefer $a_2$ to $a_1$.

**Axiom 2** (*Transitivity of preference* Zuse 1991) If one does not prefer $a_1 \in A$ to $a_2 \in A$, and does not prefer $a_2$ to $a_3 \in A$, then one does not prefer $a_1$ to $a_3$.

On this basis, the development of measurement functions must be constructed as well-formed formulas that may be used in a straightforward manner. The consistency and objectivity of the measure is best assessed by two comparison scenarios:

- I: The same manufacturing system before and after reconfiguration
- II: Two independent manufacturing systems prior to a potential reconfiguration.

The first of the two is comparatively easy. The final system may be compared to the initial system and since all else is held equal, the change in the measure's value reflects the change in the system. The measurement need only ensure that the two changes are intuitively related. The second scenario is significantly harder because the standardizing space must indeed provide a basis of comparison of the two systems. Otherwise, there is a potential of comparing “apples to oranges”. Once this basis is achieved, the measure needs to be sophisticated enough to highlight the differences of the two systems. Next, each measure implies a certain set of units and dimensions. Care must be taken that the mathematical expression of the formula does not mix these units in inadmissible ways. Finally, a good measure should enable a quantitative analysis which creates a feedback effect in an iterative design process. Recall that this last feature of a measure was used to motivate the need for a reconfigurability measure.

Together, these three sets of requirements may be summarized by the rows in Table 2 and will be used to organize the requirements adherence discussion found in “Discussion: adherence to requirements” section.

## Background: foundations of reconfigurability measurement

The composite reconfigurability and key characteristic measures presented as a contribution in the next section are best understood in the context of Fig. 2. The composite measures are algebraically built upon two sets of elemental measures already found in the literature (Farid and McFarlane 2008; Farid 2008a, 2007): reconfiguration potential and reconfiguration ease. The reconfiguration potential measures used the axiomatic design for large flexible systems knowledge base as a standardizing space model (Farid and McFarlane 2008; Farid 2007). Meanwhile, the reconfiguration ease measures used the design structure matrix as a model (Farid 2008a, 2007). Furthermore, these measurement models are constructed using a reconfigurability measurement method also previously described (Farid and McFarlane 2007; Farid 2007). While a deep treatment of these methods, models and elemental measures is not feasible here, the interested reader is referred to the background references for the necessary details and supporting discussion (Farid and McFarlane 2006a, 2007, 2008; Farid 2007, 2008a, b, 2013, 2014a, b; Viswanath et al. 2013; Baca et al. 2013). That said, it is important to recognize that because the composite measures for reconfigurability and its key characteristics are algebraically dependent on the elemental measures of reconfiguration potential and ease, their application does not require any additional data collection and can be straightforwardly calculated from the existing data models. Therefore, this section provides the most important definitions from previous works are recalled here to support the contribution of this paper in "Composite reconfigurability measures" section.

Figure 3 shows a conceptual representation of a reconfiguration process. Facilitating the potential for such a reconfiguration 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.

### Measurables and measurement methods

As shown in Fig. 2, the measurement of reconfigurability is naturally an indirect measurement process (Cerni and 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 systems 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). Furthermore, a facilitated method for their manual extraction has been previously reported (Farid and McFarlane 2007; Farid 2007). 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; Wu et al. 2013). In such a case, the measurables of production processes, resources, and interfaces can be automatically extracted.

### Reconfiguration potential 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 4** (*Transformation process* Farid and 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.

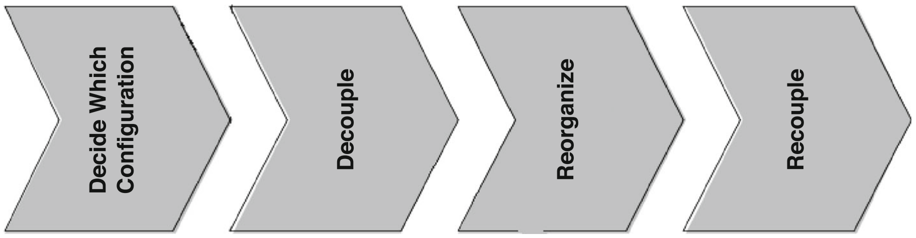


**Fig. 3** A four step reconfiguration process (Farid and Covanich 2008)

**Definition 5** (*Transportation process* Farid and 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 $b_{sy_1}$ to $b_{sy_2}$. 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 6** (*Holding process* Farid and McFarlane 2008) A material-handler and end-effector-independent process $p_{\gamma g} \in P_\gamma = \{p_{\gamma 1} \ldots p_{\gamma\sigma(P_\gamma)}\}$ that holds raw material, work-in-progress, or final products during the transportation from one buffer to another.

It is important to recognize that these production processes are *cyber-physical*. They include the physical activities of transforming and transporting material but they also include the intelligent and informatic activities that are completed by the intelligent agents and controllers that drive them (Farid and McFarlane 2008; Farid 2007).

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

$$P = J_S \odot R \tag{1}$$

where $\odot$ is "matrix Boolean multiplication" (Farid and McFarlane 2008) and $J_S$ is the production system knowledge base.

**Definition 7** (*Production system knowledge base* Farid and McFarlane 2008) A binary matrix $J_S$ of size $\sigma(P) \times \sigma(R)$ whose element $J_S(w, v) \in \{0, 1\}$ 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. $J_S$ can then be reconstructed straightforwardly from smaller knowledge bases that individually address transformation, transportation, and holding processes. $P_\mu = J_M \odot M$, $P_\eta = J_H \odot R$, $P_\gamma = J_\gamma \odot R$.$J_S$ then becomes (Farid and McFarlane 2008)

$$J_S = \left[\begin{array}{c|c} J_M & \mathbf{0} \\ \hline \multicolumn{2}{c}{J_{\bar{H}}} \end{array}\right] \tag{2}$$

where in order to account for the simultaneity of holding and transportation processes (Farid 2013)

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

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 8** (*Production system scleronomic constraints matrix* Farid and McFarlane 2008) A binary matrix $K_S$ of size $\sigma(P) \times \sigma(R)$ 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 (Farid and McFarlane 2008):

$$K_S = \left[\begin{array}{c|c} K_M & \mathbf{1} \\ \hline \multicolumn{2}{c}{K_{\bar{H}}} \end{array}\right] \tag{4}$$

where Farid (2013)

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

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

**Definition 9** (*Sequence-independent production degrees of freedom* Farid and 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:

$$DOF_S = \sigma(\mathscr{E}_S) = \sum_{w}^{\sigma(P)} \sum_{v}^{\sigma(R)} [J_S \ominus K_S](w, v) \tag{6}$$

where $A \ominus B$ operation is "boolean subtraction". Alternatively, $A \ominus B$ is equivalent to $A \cdot \bar{B}$. Note that the boolean "AND" $\cdot$ is equivalent to the hadamard product, and $\bar{B} = \text{not}(B)$. In matrix form, Eq. 6 can be rewritten in terms of the Frobenius inner product (Abadir and Magnus 2005).

$$DOF_S = \langle J_S, \bar{K}_S \rangle_F = tr(J_S^T \bar{K}_S) \tag{7}$$

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 and McFarlane 2008).

**Definition 10** (*Sequence dependent production degrees of freedom* Farid and McFarlane 2008) The set of independent production strings $z_{\varphi\psi} = e_{w_1 v_1} e_{w_2 v_2} \in \mathscr{Z}$ of length 2 that completely describe the production system language. Their number is given by:

$$DOF_\rho = \sigma(Z) = \sum_{\varphi}^{\sigma^2(P)} \sum_{\psi}^{\sigma^2(R)} [J_\rho \ominus K_\rho](\varphi, \psi) \tag{8}$$

where $J_\rho$ and $K_\rho$ are defined below.

**Definition 11** (*Rheonomic production system knowledge base* Farid and McFarlane 2008) A binary matrix $J_\rho$ of size $\sigma^2(P) \times \sigma^2(R)$ whose element $J_\rho(\varphi, \psi) \in \{0, 1\}$ are equal to one when string $z_{\varrho,\psi}$ exists. It may be calculated directly as

$$J_\rho = \left[J_S \cdot \bar{K}_S\right] \otimes \left[J_S \cdot \bar{K}_S\right] \tag{9}$$

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 12** (*Rheonomic production constraints matrix* $K_\rho$ Farid and McFarlane 2008) A binary constraints matrix of size $\sigma^2(P) \times \sigma^2(R)$ whose elements $K_\rho(\varphi, \psi) \in \{0, 1\}$ are equal to one when string $z_{\varphi\psi}$ is eliminated.

Refs. Farid (2007) and Farid and McFarlane (2008) detail how it may be calculated.

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 $L = \{l_1, \ldots, l_{\sigma(L)}\}$. Each product $l_i$ has its associated set of product events $e_{x_{li}} \in E_{li}$ which when all are completed result in a fully manufactured product.

**Definition 13** (*Product event* Farid 2008b) 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 14** (*Product transformation feasibility matrix* $\Lambda_{\mu i}$ Farid 2008b) A binary matrix of size $\sigma(E_{l_i}) \times \sigma(P_\mu)$ whose value $\Lambda_{\mu i}(x, j) = 1$ if $e_{x_{li}}$ realizes transformation process $p_j$.

**Definition 15** (*Product transportation feasibility matrix* $\Lambda_{\gamma i}$ Farid 2008b) A binary row vector of size $1 \times \sigma(P_\gamma)$ whose value $\Lambda_{\gamma i}(g) = 1$ 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).

$$DOF_{LM} = \langle \Lambda_{ML} \cdot J_M, \bar{K}_M \rangle_F \tag{10}$$

$$DOF_{LH} = \langle \Lambda_{HL} \cdot J_{\bar{H}}, \bar{K}_{\bar{H}} \rangle_F \tag{11}$$

where

$$\Lambda_{ML} = \bigvee_{i}^{\sigma(L)} \bigvee_{x}^{\sigma(E_L)} \Lambda_{\mu i}^T \mathbf{1}^{\sigma(M)T} \tag{12}$$

$$\Lambda_{HL} = \left[ \left( \bigvee_{i}^{\sigma(L)} \Lambda_{\gamma i} \right) \otimes \mathbf{1}^{\sigma(P_\eta)T} \right]^T \mathbf{1}^{\sigma(R)T} \tag{13}$$

The intuitive form of product degrees of freedom in Eqs. 10 and 11 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 2008b).

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 relative to the desired set of reconfigurations.

### Reconfiguration ease measures

In this subsection, modularity is addressed as one of the key characteristics of reconfigurable manufacturing systems. As shown in Fig. 4, the decoupling and coupling of products and resources must be considered not just physically but at all of the ISA-S95 control levels. This specifically allows the

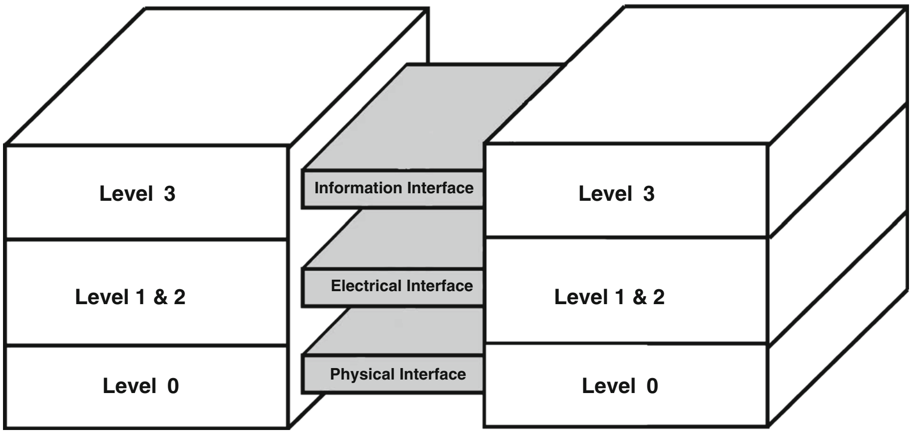
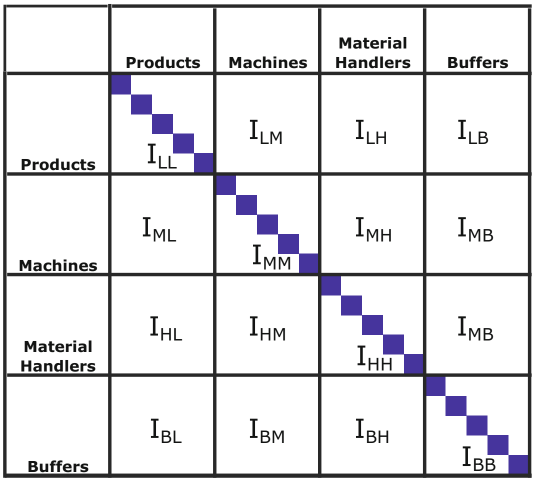


**Fig. 4** Conceptual representation of multi-level interfaces of production resources and products (Farid 2008a)



| | 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 | $I_{HL}$ | $I_{HM}$ | $I_{HH}$ | $I_{MB}$ |
| Buffers | $I_{BL}$ | $I_{BM}$ | $I_{BH}$ | $I_{BB}$ |

**Fig. 5** Production design structure matrix (Farid 2008a)

inclusion of informatic interations between intelligent agents in Level 3.

Here, the production design structure matrix (Farid 2008a) 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 Fig. 5. The associated measure of modularity is given by Farid (2008a)

$$\Gamma = \left[\frac{a_d}{V_d}\right] - \left[\frac{a_o}{V_o}\right] \tag{14}$$

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 2008a). From this foundation, the discussion can turn to the introduction of the composite reconfigurability measures.

## Composite 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 structurally-dependent key characteristics: integrability, convertibility, and customization (Mehrabi et al. 2000). Each of these is now discussed in turn.

### Integrability

As the second of four key reconfigurability characteristics, it has been described as Mehrabi et al. (2000):

*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 Fig. 3, 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:

$$\mathscr{I} = \sum_{\psi}^{\sigma^2(R)} \left[1 - \frac{a_{o\psi}}{V_{o\psi}}\right] \sum_{\varphi}^{\sigma^2(P)} [J_\rho \ominus K_\rho](\varphi, \psi) \tag{15}$$

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.

### Convertibility

The convertibility of a manufacturing system can be addressed similarly. It is described as Mehrabi et al. (2000):

*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. The coupling between the product and resources quantifies the reconfiguration ease as a second step.

In this work, the convertibility measure is the sum of two components: transformation and transportation convertibility. This dichotomy arises from Eqs. 10 and 11 which account for the fact that a product's feasibility towards transformation and transportation resources is fundamentally different (Farid 2008b, 2013). The feasibility of a material handler towards a given product primarily depends on fixturing. Meanwhile, the feasibility of a product toward a transformation resources requires fixturing, tooling as well as detailed information of process plans. Naturally, in addition to the feasibility concerns, the coupling between products and transformation resources is typically much stronger than the coupling between products and transportation resources. Consequently, two convertibility measures are developed. The effort required for the second step can be quantified using the modularity of the resource–product pair. The measures for transformation and transportation convertibility respectively are:

$$\mathscr{C}_M = \sum_{i}^{\sigma(L)} \sum_{j}^{\sigma(P_\mu)} \sum_{k}^{\sigma(M)} \left[1 - \frac{a_{oik}}{V_{oik}}\right] \left[\Lambda_{Mi} \cdot J_M \cdot \bar{K}_M\right](j,k) \tag{16}$$

$$\mathscr{C}_H = \sum_{i}^{\sigma(L)} \sum_{\varrho}^{\sigma(P_{\bar{\eta}})} \sum_{v}^{\sigma(R)} \left[1 - \frac{a_{oiv}}{V_{oiv}}\right] \left[\Lambda_{Hi} \cdot J_{\bar{H}} \cdot \bar{K}_{\bar{H}}\right](\varrho,v) \tag{17}$$

where Farid (2013)

$$\Lambda_{Mi} = \left[\bigvee_{x}^{\sigma(E_L)} \Lambda_{\mu i}\right]^T \mathbf{1}^{\sigma(M)T} \tag{18}$$

$$\Lambda_{Hi} = \left[\Lambda_{\gamma i} \otimes \mathbf{1}^{\sigma(P_\eta)T}\right]^T \mathbf{1}^{\sigma(R)T} \tag{19}$$

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 sceleronomic constraints and product–resource coupling.

### 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. (2000):

*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:

$$\mathscr{C} = \frac{DOF_{LM} + DOF_{LH}}{DOF_S} \tag{20}$$

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.

### Reconfigurability

Given the measures for the four the key characteristics of modularity, integrability, convertibility and customization, a measure for reconfigurability can be synthesized. As mentioned in Definition 2, 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.

$$R = \mathscr{I} + \mathscr{C}_M + \mathscr{C}_H \tag{21}$$

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.

As derived, these measures give absolute values of reconfigurability and its key characteristics for a given manufacturing system. That said, in the context of interpreting the measurement results, it is often useful to normalize the measurements by an *ideal* version of the same system. Such a system would have no scleronomic constraints, the minimal rheonomic constraints, and no coupling on the off-block diagonal of the production design structure matrix. Intuitively speaking, such a theoretical system would have all of its existing capabilities available and would require no reconfiguration effort to change between configurations.

## An illustrative example

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 and McFarlane 2006a, b, c, 2007, 2008; Farid and Covanich 2008; Farid 2007, 2008a, b, 2013). Here, the essential aspects of the test case are included before presenting the associated quantitative results.

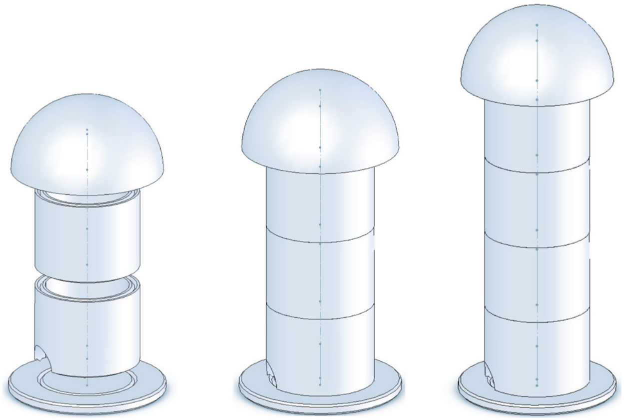


**Fig. 6** CAD model of starling bird feeders (Farid 2007, 2008a, b; Farid and McFarlane 2008)

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 a 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 6 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.

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 7 shows the initial configuration, Fig. 8 adds a second machining station, and Fig. 9 makes all three value-adding resources redundant. 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}. $P_\eta = \{m_i m_j, m_i b_k, b_k m_i, b_k b_l\} \forall i, j = 1, 2, 3, k, l = 1, 2$. $P_\gamma$ = {Small Radial, Big Radial, Axial}. The production processes and resources for the other system configurations may be determined analogously. Figure 10 presents the transformation, transportation,

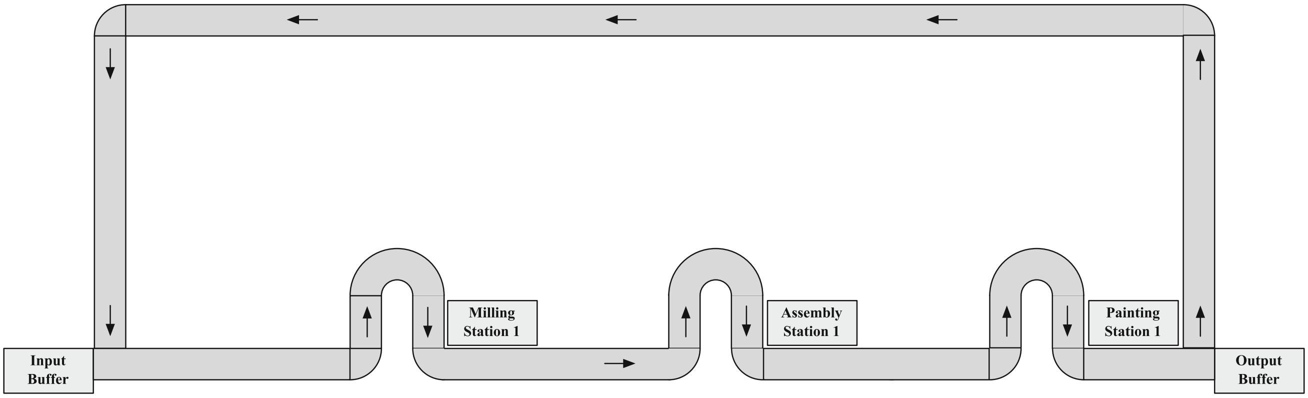


**Fig. 7** Phase I of starling manufacturing system (Farid 2007, 2008a, b; Farid and McFarlane 2008)

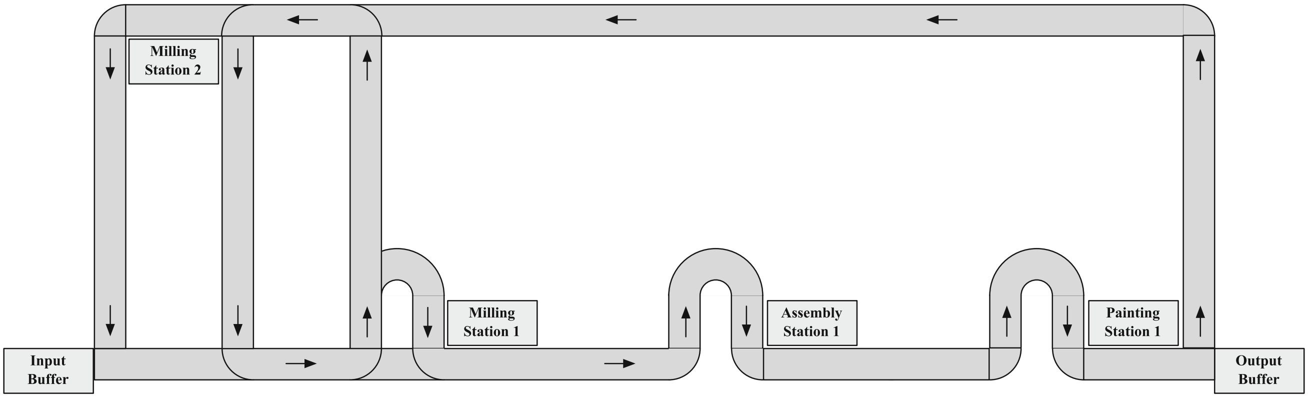


**Fig. 8** Phase II of starling manufacturing system (Farid 2007, 2008a, b; Farid and McFarlane 2008)

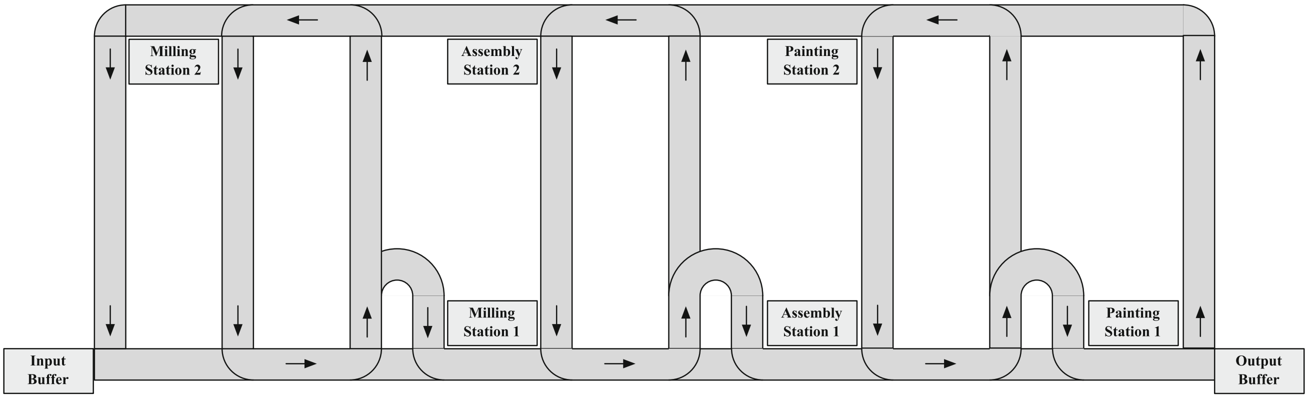


**Fig. 9** Phase III of starling manufacturing system (Farid 2007, 2008a, b; Farid and McFarlane 2008)

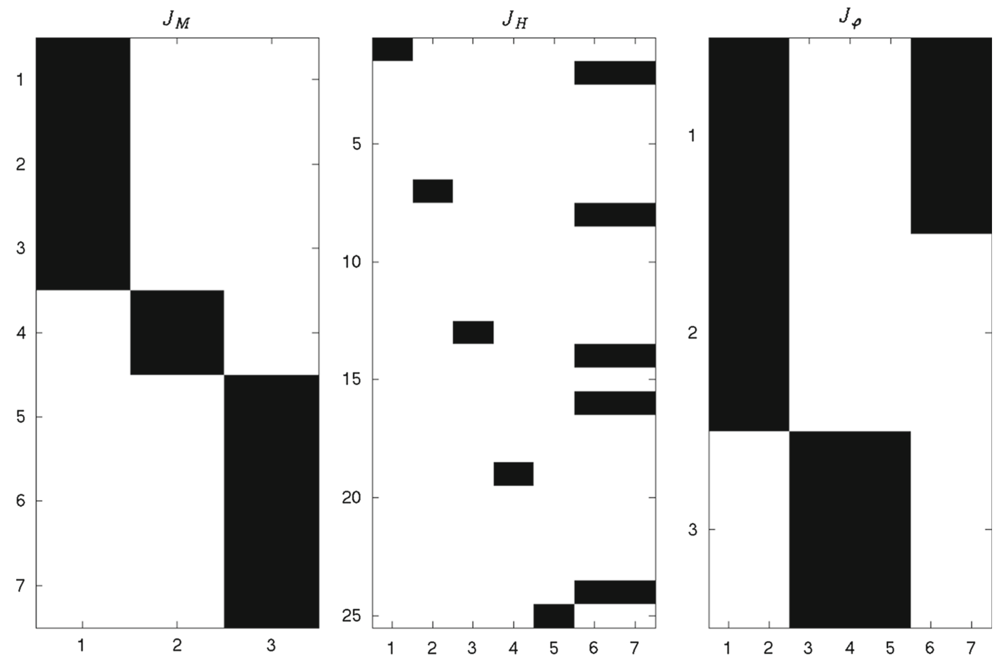


**Fig. 10** Starling manufacturing system knowledge bases (Farid and McFarlane 2008; Farid 2007, 2008b, 2013)

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 previously identified minimal constraints (Farid and McFarlane 2008). 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 and McFarlane (2008), Farid (2007, 2008b). The production design structure matrix for Stage I is taken as given from the worked example in Farid (2007, 2008a) and is shown graphically in Fig. 11. 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 scleronomic constraints, the minimal rheonomic constraints, and no coupling on the off-block diagonal of the 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 respectively. This is to be expected because products and resources are typically much more coupled than resources

**Fig. 11** Starling manufacturing system production design structure matrix (Farid 2007, 2008a)

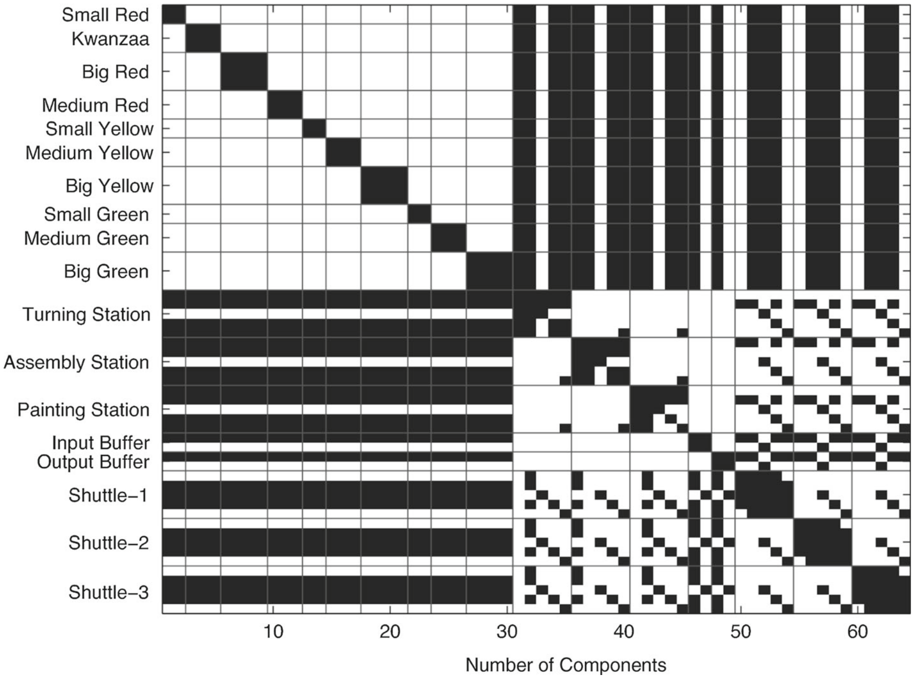


**Table 1** Reconfigurability and its key characteristics for starling manufacturing system

| | Stage I | Stage II | Stage III |
|---|---|---|---|
| Integrability | 134.92 | 348.72 | 2,475 |
| | (0.8705) | (0.8675) | (0.8980) |
| Transformation | 10.4 | 16.4 | 20.8 |
| Convertibility | (0.20) | (0.20) | (0.20) |
| Transportation | 76 | 150 | 538 |
| Convertibility | (0.38) | (0.3846) | (0.3927) |
| Customization | 1 | 1 | 1 |
| Reconfigurability | 221.32 | 515.12 | 3033.8 |
| | (0.5438) | (0.5894) | (0.7172) |

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 systems 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.

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 modularity and degrees of freedom. The combination of 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.

## Discussion: adherence to requirements

In addition to the quantitative demonstration of the previous section, it is beneficial to discuss the measures of reconfigurability and its key characteristics qualitatively with respect to the requirements identified in "Reconfigurability measurement requirements in automated manufacturing systems" section. As before, the discussion addresses requirements for reconfigurability description, requirements for measurement, and requirements for manufacturing systems. Table 2 preemptively summarizes the conclusions of the discussion.

**Table 2** Adherence of DOF, modularity, and composite measures to reconfigurability measurement requirements

| | DOF measures | Modularity measure | Composite measures |
|---|---|---|---|
| Reconfigurability description | | | |
| System boundary | ● | ● | ● |
| System structure | ◑ | ◐ | ● |
| Desired reconfiguration | ● | ● | ● |
| Reconfiguration ease | ○ | ● | ● |
| Manufacturing systems | | | |
| Resources and processes | ● | ◐ | ● |
| Heterogeneous processes | ◑ | ◐ | ● |
| Heterogeneous interfaces | ○ | ● | ● |
| Degree of distribution | ◑ | ◐ | ● |
| Heterogeneous control | ◑ | ◐ | ● |
| Measurement process | | | |
| Measurables | ◑ | ◐ | ● |
| Methods | ● | ● | ● |
| Models | ◑ | ◐ | ● |
| Measures | ◑ | ◐ | ● |
| Reconfigurability property | ● | ● | ● |

○—unaddressed, ◑—partially addressed, ◐—complementarily addressed, ●—addressed

### Requirements for reconfigurability description

The complementary nature of production degrees of freedom as reconfiguration potential measures and modularity as a reconfiguration ease measure provide for an intuitive basis to describe reconfigurability. The underlying models of the production system knowledge base and design structure matrix respected the system boundary and explicitly addressed the desired set of reconfigurations. Additionally, the modularity measures specifically addressed the ease of reconfiguration. Finally, the two groups of measures together addressed system structure as stated in Definition 2. The axiomatic design knowledge base addresses the first two points in the definition while the production design structure matrix addresses the latter two.

### Suitability requirements for manufacturing systems

Together, the production degree of freedom and modularity measures addressed all the suitability requirements specific to manufacturing systems. The production system knowledge base addressed the heterogeneity of production system resources and processes. In the meantime, the level of abstraction allowed for these processes to occur in many energy domains and have different types of associated control functions. The product feasibility matrices correspondingly addressed multiple product variants. In the meantime, the production system design structure matrix also addressed the heterogeneity of production resources and product variants and recognized that the interfaces between them could be material, energy, information and space. Similarly, the associated control functions could be parameterized and included within the production design structure matrix as a data structure.

### Requirements for measurement

Finally, the complementary nature of the production degree of freedom and modularity measures address the five requirements for measurement. Each of these is addressed in turn.

#### *Measurables and methods*

The four types of measurables: production processes, resources, their components, and their interfaces completely cover the description of system structure. The first two of these are captured in the production knowledge base model and provide a quantitative description of reconfiguration potential. The latter set of measurables are captured in the production design structure matrix model and provide a quantitative description of reconfiguration ease. It is worth noting that the differentiation of production processes is an ontological activity (Gasevic et al. 2009). Many independent research fields (product design (Hirtz et al. 2002), computer aided process planning (Carr 2002; McFarlane et al. 2002), artificial intelligence (Gasevic et al. 2009) have devoted extensive effort toward its development. In product design, efforts have been made to develop a basis of functions; implying that the ontology is of minimal size but maximal completeness (Hirtz et al. 2002). In manufacturing, the STEP, STEP-NC, and Rosetta-Net "Standards" have been developed (Carr 2002; McFarlane et al. 2002). While these approaches are helpful, it is likely that an all-inclusive production process ontology would be too "heavy" for the measurement requirements of a given enterprise. Instead, a lightweight "home-grown" situation-specific ontology would be more likely to be developed using any of a number of open-source or proprietary ontology development tools (Wikipedia 2007). That said, a more complete ontology would be required to compare the reconfigurability of two independent manufacturing systems. With respect to components and interfaces within resources, a level of consistency must be applied in the physical decomposition. Previous work (Farid and McFarlane 2007; Farid 2008a) has given the first and second levels of decomposition in the production design structure matrix. Further decompositions would naturally depend on the method of identifying these measurables be it in a manual or automated fashion. A manual approach has been discussed in Farid and McFarlane (2007). Meanwhile, an automated approach as mentioned previously would depend on available data be they CAD diagrams, process plans, or SysML/UML diagrams. In either case, the data would need to be consistently described and the extraction process (be it manual or automated) would need to be the same in order for the reconfigurability of two independent manufacturing systems to be completed.

### *Models*

The models used as part of the reconfigurability measurement process were the production system knowledge base and design structure matrix. In the presence of a consistent approach to identifying their rows and columns, they each provide a straightforward standardizing space to describe (1) the allocation of production processes to production resources, (2) the interrelationships between production resources.

### *Measures*

The reconfigurability measures themselves fell into three categories: production degree of freedom measures that describe reconfiguration potential, a modularity measure to describe reconfiguration ease, and composite measures that describe reconfigurability itself and its key characteristics. They are addressed in terms of measurement scales, intuitiveness, computational simplicity, and consistency of units.

**Table 3** Units of measure for reconfigurability, its key characteristics, its potential and its ease

| Measure | Units |
|---|---|
| $DOF_S$ | Processes/resource |
| $DOF_\rho$ | (Processes/resource)$^2$ |
| Product DOF | (Events/product)(processes/resource) |
| Modularity | (Interactions)/(components)$^2$ |
| Integrability | (Interactions)/(components)$^2$(processes/resource)$^2$ |
| Convertibility | (Interactions)/(components)$^2$· (Events/product)(processes/resource) |
| Customization | Dimensionless |
| Reconfigurability | (Interactions)/(components)$^2$(processes/module)$^2$ |

In regards to measurement scales, the production degree of freedom measures exist on an absolute scale (Stevens 1946). Thus, they permit all types of statistics (Stevens 1946). Meanwhile, the modularity measure forms a ratio scale and so permit all types of statistics except for additivity (Stevens 1946). Therefore, the composite measures also form a ratio scale.

In regards to their intuitiveness, it is very difficult to imagine that the measures do not adhere to the two measurement axioms. That is, it is very difficult to imagine a scenario in which a production system has greater capabilities but fewer degrees of freedom. Similarly, it is very difficult to imagine a more cohesive and less coupled production system resulting in a lower measure of modularity. Consequently, the same can be applied to the intuitive notions of reconfigurability and its key characteristics.

In regards to computational simplicity, the measurement of reconfigurability as a physical model is data intensive. In a sense, a virtual model of the production system must be constructed prior to any calculation. With this in mind, it is clear that the production degrees of freedom are computationally straightforward and require a count on the order of $\sigma(P)\sigma(R)$ in the sequence independent case and $\sigma^2(P)\sigma^2(R)$ in the sequence dependent case. Similarly, the modularity measures are also computationally straightforward and require simple sums that count the elements in various regions of the production design structure matrix. This count is on the order of $\sigma^2(C)$ where $C$ is the number of components defined in all resources and products. Therefore, the illustrative example, while of modest size, does not limit the scalability to a full industrially-sized problem.

In regards to measurement units, it is worth noting that the production degrees of freedom, modularity, and composite measures are entirely consistent. These are straightforwardly determined by Eqs. 15, 16, 17, and 20 and have an intuitive appeal. They are summarized in Table 3.

Note that in this work, it is permissible to consider product events as a type of process and products and resources as a type of module thus allowing the consistency of units in the reconfigurability measure.

Finally, the production degree of freedom, modularity, and composite measures offer significant design feedback. Reconfiguration potential is improved in three ways: (1) increasing the redundancy of production processes, (2) increasing the flexibility of a given resource, (3) allowing any two combinations of production capabilities (i.e. degrees of freedom) to follow each other. Reconfiguration ease is improved by eliminating the interactions between resources and their components. The composite measures of reconfigurability and its key characteristics utilize a combination of the above.

## Conclusion

This work has built upon the recently developed reconfigurability measurement process to produce measures of reconfigurability and its key characteristics of integrability, convertibility, and customization as applied to 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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