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Abstract: In recent years, many design approaches have been developed for automated manufacturing systems in the fields of reconfigurable manufacturing systems (RMSs), holonic manufacturing systems (HMSs), and multi-agent systems (MASs). One of the principle reasons for these developments has been to enhance the reconfigurability of a manufacturing system, allowing it to adapt readily to changes over time. However, to date, reconfigurability assessment has been limited. Hence, the efficacy of these design approaches remains inconclusive. This paper is the first of two in this issue to address reconfigurability measurement. Specifically, it seeks to address 'reconfiguration potential' by analogy. Mechanical degrees of freedom have been used in the field of mechanics as a means of determining the independent directions of motion of a mechanical system. By analogy, manufacturing degrees of freedom can be used to determine independent ways of production. Furthermore, manufacturing degrees of freedom can be classified into their production and product varieties. This paper specifically focuses on the former to measure the product-independent aspects of manufacturing system 'reconfiguration potential'. This approach will be added to complementary work on the measurement of 'reconfiguration ease' so as to form an integrated reconfigurability measurement process described elsewhere [**1–5**].

Keywords: reconfigurability, reconfigurable manufacturing systems, manufacturing degrees of freedom, production degrees of freedom, holonic manufacturing systems, multi-agent systems

1 INTRODUCTION

In the 1990s, manufacturing became increasingly characterized by continually evolving and ever more competitive marketplaces. The effective implementation of lean manufacturing principles had freed excess capacity in many instances, and thus gave consumers greater influence over the quality, quantity, and variety of products [**6**, **7**]. In order to stay competitive, manufacturing firms had to respond with a high variety of products of increasingly short product life cycle [**8**, **9**]. These dual requirements of mass-customization and short product life cycles cause a multidimensional engineering management problem that enterprises have to find ways to address. One particularly pertinent problem is the need quickly and incrementally to adjust production capacity and capability. As the continually growing variety of products are introduced, ramped up, phased out, and finally made obsolete, shop floors have to find efficient ways to reallocate the capabilities of production resources to the product variants that need them most. The realization of these incremental changes is not just a tooling and fixturing set-up problem; it also requires extensive change in control code and production planning systems. The problem is further exacerbated because investment into these production systems is rationalized on the basis that they produce specific products at a certain throughput to yield the desired return.

To fulfil the needs of enterprises with extensive automation, reconfigurable manufacturing systems (RMSs) have been proposed as a set of possible solutions [**10**]. They are defined as follows.

Definition 1.1. Reconfigurable manufacturing system (RMS): '[a system] designed at the outset for rapid change in structure, as well as in hardware

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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.' [**11**]

RMSs may be contrasted with dedicated manufacturing lines and flexible manufacturing systems. The former consists of inexpensive fixed automation equipment and provides a single product at a high capacity; hence, it is ill equipped to support small batch size, short life cycle, customized products. Flexible manufacturing systems, on the other hand, can produce the variety, albeit at the price of a large capital investment and a significantly reduced throughput; hence, the cost per part is often prohibitively high from both a fixed and variable cost point of view. RMSs seek to achieve the variety and low cost by incrementally adding capacity and functionality. In this way, new capabilities are added only when needed and the manufacturing system is not over-designed with capabilities that may be left unused [**11**].

Over the last decade, many technologies and design approaches have been developed to enable reconfigurability in manufacturing systems. These have included modular machine tools [**12–17**], distributed automation [**18**, **19**], multi-agent systems (MASs) [**20**, **21**], and holonic manufacturing systems (HMSs) [**7**, **22–25**]. While initial efforts to assess these design approaches have been reported [**26–29**], numerous authors have identified the need for a holistic reconfigurability measurement process [**5**, **30–35**]. Hence, it remains inconclusive whether the resulting designs achieve their intended level of reconfigurability. Furthermore, the absence of reconfigurability measurement has prevented the use of iterative design processes that may gradually achieve optimal results. Instead, one-off design approaches that do not build upon previous work are often investigated. This present paper seeks partially to address this need by specifically focusing on production degrees of freedom as a product-independent measure of a manufacturing system's 'reconfiguration potential'.

This paper follows a four-part discussion. Section 2 provides three elements for the synthesis of reconfiguration potential measures: a discussion in measurement processes, axiomatic design models, and mechanical degrees of freedom. Section 3 then contextualizes these elements for manufacturing systems by drawing an analogy with mechanical systems. Next, section 4 develops production degrees of freedom as reconfigration potential measures. Section 5 concludes with the measures' application to an illustrative example. Prior to proceeding, this paper restricts its discussion to the shop-floor activities of automated manufacturing system as defined in Levels 0–3 of ISA-S95 [**36**]. Furthermore, it defines reconfigurability as follows.

Definition 1.2. Reconfigurability [**4**, **5**]: the ability to add, remove, and/or rearrange in a timely and cost-effective manner the components and functions of a system that can result in a desired set of alternate configurations.

2 BACKGROUND

In order to proceed with the development of production degrees of freedom, an understanding of three fundamental elements is required: (indirect) measurement processes, axiomatic design models, and mechanical degrees of freedom. Each is introduced here.

2.1 Measurement processes

Generally speaking, a measurement process requires:

(a) identification of structure-dependent measurables;
(b) methods for measuring the measureables;
(c) models for describing/modelling a system;
(d) identification of structure-dependent properties;
(e) formulaic measures of relating those models to those properties.

The requirements can be graphically represented as a sequential data flow diagram – see Fig. 1. Implicitly, as an objective, a set of measured properties needs to be identified. In most measurement processes, these properties are distinct from the system measureables that must be extracted from the system of interest with a set of measurement methods. If the measured property is too complex for direct measurement, the measurement must be inferred [**37**]. This requires that the measureables be related using a set of models. Finally, the mathematical theory of measurement [**38**] requires a set of measures. These measures are a specific class of mathematical functions and serve to convert related measureables to the final measured property [**39**]. The next sub-sections highlight models and measures that will be useful in the synthesis of a reconfiguration potential measurement process.

2.2 Axiomatic design models

Axiomatic design is a structured systems design method that decouples a system's design parameters from its functional requirements [**40**, **41**]. While axiomatic design was initially applied to machine design [**40–42**], its applications have become

Fig. 1 A generic measurement process

increasingly diverse [**41**, **43–52**]. Most interestingly, it has received attention in the design of lean [**53–56**], cellular [**57**], flexible [**58**, **59**], and holonic manufacturing systems [**60**]. It is particularly useful because it aids the design to define the system structure using a formal theoretical framework based upon axioms and design matrices [**40**, **41**, **61–66**]. Specifically, it relates a system's functional requirements, *FR*, to its design parameters, *DP*, in a 'design equation' with a binary design matrix, *DM*.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} DM_{11} & DM_{12} & DM_{13} \\ DM_{21} & DM_{22} & DM_{23} \\ DM_{31} & DM_{32} & DM_{33} \end{bmatrix} \circledast \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \quad (1)$$

where the aggregation operation $\circledast$ is defined as follows.

Definition 2.1. Aggregation operator $\circledast$[**5**]: given Boolean matrix A and sets B and C, $C = A \circledast B$ is equivalent to

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

In such a way, the design equation clarifies which design parameters fulfil each of the system's functional requirements. For a special class of system called 'large flexible systems', a given functional requirement can be fulfilled by a choice of one or more design parameters [**41**]. In such a case, the design equation becomes

$$FR = J \odot DP \quad (3)$$

where J is a binary matrix called a 'knowledge base', and the 'matrix Boolean multiplication' operator $\odot$ is defined as follows.

Definition 2.2. Matrix Boolean multiplication $\odot$ [**5**]: given sets or Boolean matrices B and C and Boolean matrix A, $C = A \odot B$ is equivalent to

$$C(i,k) = \bigvee_j A(i,j) \wedge B(j,k) \quad (4)$$

Between the design matrix and the knowledge base, axiomatic design provides for two comprehensive ways of assigning system behaviour (in terms of functional requirements) to system components (in terms of design parameters). This characteristic addresses an important aspect of modelling system structure that can be particularly useful in the synthesis of a reconfiguration potential measurement process.

2.3 Mechanical degrees of freedom

The concept of degrees of freedom has been used extensively in many disciplines, including statistics [**67**], statistical mechanics [**68**], and mechanics [**69**]. The definition as applied to the fields of mechanics and machine design is most relevant here.

Definition 2.3. Mechanical degrees of freedom: the set of independent generalized coordinates that completely define the location and orientation of each body in the system [**69**].

This measure has been used to define an object's modes of linear and rotational motion. It has also been used to study how these modes change when two or more bodies are combined [**69**]. This measurement has facilitated the design of kinematic couplings, allowing complex machines to be constructed from more simple ones [**70**].

The measure of mechanical degrees of freedom (DOF) is given by [**69**]

$$DOF_{\text{mech}} = n_{\text{d}} n_{\text{l}} - n_{\text{k}} \quad (5)$$

where n_{d} is the number of spatial dimensions, n_{l} is the number of mechanical links, and n_{k} is the number of holonomic spatial constraints of the form

$$[K_1(\boldsymbol{x},\tau), K_2(\boldsymbol{x},\tau), \ldots, K_{n_k}(\boldsymbol{x},\tau)] = \mathbf{0} \quad (6)$$

where $\boldsymbol{x}$ is the spatial coordinates vector and τ is time. The constraints are said to be either sceleronomic or rheonomic when they are either time-independent or time-dependent, respectively [**69**]. While equation (5) is the typical form for the calculation of mechanical degrees of freedom, it can be written more generally as

$$DOF_{\text{mech}} = \sum_i^l (n_{\text{di}} - n_{\text{ki}}) \quad (7)$$

for each link i, $n_{\text{di}} = n_{\text{d}}$ and $n_{\text{k}} = \sum_i^l n_{\text{ki}}$. Furthermore, if the number of dimensions and constraints per link (n_{di} and n_{ki}, respectively), is replaced with a pure count of those dimensions and constraints, equation (7) becomes

$$DOF_{\text{mech}} = \sum_i^l \sum_j^{n_{\text{d}}(i)} (x_{ij} - k_{ij}) \quad (8)$$

where x_{ij} and k_{ij} indicate, respectively, the presence of a spatial coordinate or constraint for the ith link and the jth dimension.

A manufacturing degrees of freedom measure could have such a general functional form, although the variables of interest would have to be changed from dimensions and links. Instead, they can be replaced with their manufacturing analogues.

3 MECHANICAL AND MANUFACTURING SYSTEMS: AN ANALOGY

Given the background of the previous section, the models of axiomatic design and the mechanical degrees of freedom measure can be translated into a manufacturing system context by context.

Table 1 Mechanical and manufacturing system analogy

Mechanical	Production
State: continuous	State: discrete
State change: leads to motion	State change: leads to production
State evolution: time driven	State evolution: event driven
Motion is: rotation translation	Production is: transformation transportation
Coordinates: dimension and link	Events: process and resource

For axiomatic design, the following analogy is constructed straightforwardly

$$\begin{aligned} &\text{Functional requirements} : \text{Design parameters} \\ &\text{Production processes} : \text{Production resources} \end{aligned} \tag{9}$$

where the first part of the analogy describes 'what' the system does and the second describes 'how' it does it. A production system has two types of process: transformation and transportation, defined as follows.

Definition 3.1. Transformation process: a machine-independent, manufacturing technology-independent process $p_\mu \in P_\mu$ that transforms raw material or work-in-progress to a more final form.

Definition 3.2. Transportation process: a material-handler-independent process $p_\eta \in P_\eta$ that transports raw material, work in progress, or final goods between buffers.

Similarly, production resources R may be classified into value-adding machines M, independent buffers B, and material handlers H. The set of buffers $B_S = M \cup B$ is also introduced for later simplicity. In the case of distributed manufacturing systems, this analogy conforms to the design equation in equation (3). However, when a system has one or more centralized controller resources Q (e.g. PLC's centralized schedulers/dispatchers), the production system must first be translated into an equivalent without centralized controllers through the use of a binary aggregation matrix

$$\bar{R} = A \circledast R \tag{10}$$

where $R = M \cup H \cup B \cup Q$ and $\bar{R}$ are aggregations of the primary resources and centralized controllers. This translation allows for the straightforward usage of a modified design equation

$$P = J_S \odot [A \circledast R] \tag{11}$$

At the most basic level, a mechanical system is defined by its kinematics which is described by links and coordinates [**69**]. Links make up the physical composition of a mechanical system. Similarly, manufacturing systems are composed of (production) resources. Coordinates are used to express the time-evolution of a continuous state which results in motion. Analogously, in manufacturing systems, events describe the event-based evolution of a discrete state which results in the incremental progression of production. Cassandras and Lafortune [**71**] have previously drawn this analogy between coordinates for time-driven systems and events for event-driven systems. Kinematic state changes can be further classified as either rotational or translational. Analogously, state changes in production are the result of either transformation or transportation processes. Finally, when analysing multi-body mechanical systems, the number of coordinates is calculated based upon the number of combinations of dimensions and links [**69**]. For example, a fully free three-link system has 18 degrees of freedom: six dimensions for each of the three links. The completion of the analogy suggests that production system degrees of freedom would come from the feasible combinations of processes (transformation and transportation) and their associated resources. For degrees of freedom, Table 1 summarizes the analogy between mechanical and manufacturing systems.

Based upon these analogies, a final analogy can be made between reconfiguration potential and mechanical degrees of freedom. From the reconfigurability definition, reconfiguration potential can be interpreted in two ways:

(a) the ability of a system to simultaneously hold multiple desired configurations;
(b) the ability of a system to change to a desired set of alternate configurations.

In either case, a degrees of freedom approach appears as a suitable starting point for a reconfiguration potential measure. Firstly, mechanical degrees of freedom describe the kinematic configuration of the system. By analogy, a manufacturing degrees of freedom measure can be used to describe the production configuration of a manufacturing system. Following the reconfigurability definition, this configuration is described by components such as production resources and functions such as production processes. Secondly, a mechanical degrees of freedom measure gives the number of available options for motion. Similarly, a manufacturing degrees of freedom measure could be used to give the number of available options for production. Such a number would indicate the system's multiple configurations.

It would also change as the system underwent successive reconfigurations. In summary, a degrees of freedom approach is suitable for measuring reconfiguration potential because it describes the elements of a system and how they may be combined into numerous productive configurations.

Despite the strong analogy between mechanical and manufacturing systems and their respective degrees of freedom measures, there exist three limitations on its applicability that give rise to a three-tiered taxonomy of manufacturing degrees of freedom. First, manufacturing systems exist purely to produce some sort of product. In contrast, a mechanical system can be conceived and analysed without predefining the objects upon which it acts. The dependence on a system's product line causes the classification into production and product degrees of freedom. Second, mechanical degrees of freedom are generally considered a static property unless there exist some rheonomic [**5**] (time-dependent) constraints. In contrast, manufacturing systems must consider the sequence of processes because of the ultimate objective sequentially to produce a product. Therefore, at the next level of decomposition, manufacturing degrees of freedom are differentiated into their sequence independent varieties: scleronomic and rheonomic. A final limitation arises from the relative importance of transformation and transportation processes. The remainder of this paper addresses the left half of this taxonomy.

4 PRODUCTION DEGREES OF FREEDOM

The development of production degrees of freedom closely follows the taxonomy above over six subsections. While at first view this indicates significant complexity, in actuality, the development of all the measures is a variation on a theme of three basic elements. First, the combination of resources and processes are captured in an axiomatic design knowledge base in order to form the events of a fully free manufacturing system. Next, a set of holonomic constraints are used to eliminate events from the event set. Finally, the difference between the number of events and constraints determine the number of degrees of freedom in the system.

4.1 Transformation degrees of freedom

The analogy drawn in section 3 suggests that transformation degrees of freedom depend on two production system variables: the set of transformation processes $P_\mu = \{p_{\mu 1}, \ldots, p_{\mu\sigma(P_\mu)}\}$ and the set of transformation machines $M = \{m_1, \ldots, m_{\sigma(M)}\}$ which realize them. Note that the $\sigma()$ operator gives the size of a set. The behaviour N_{m_k} of a machine m_k can be described as a Petri net [**72**]

$$N_{m_k} = \{S_{m_k}, T_{m_k}, F_{m_k}\} \tag{12}$$

where S_m is a set of places, T_m is a set of transitions, and F_m is a set of flow relations. Similarly, the behaviour of a transformation process p_{μ_j} may be described as a net

$$p_{\mu_j} = \{S_{\mu_j}, T_{\mu_j}, F_{\mu_j}\} \tag{13}$$

More practically, a transformation process requires a forming function (e.g. milling, drilling, assembly), a holding function (e.g. fixturing, clamping), and a number of control functions (execution, scheduling, planning, dispatching, and sensing.) Of these, the forming function $t_{\mu_{j\pi}}$ may be treated as the principal function without which the process ceases to have a transformational sense.

To continue the analogy in Table 1, coordinates, as the feasible combination of link and dimension must be translated into events which are the feasible combination of process and machine. In other words, an event $e_{\mu_j m_k} \in E_{\mu M}$ (in the discrete event system sense [**71**]) can be defined for each feasible combination of transformation process $p_{\mu j}$ being realized by machine m_k. At this point, an axiomatic design knowledge base $J_{\rm M}$ may be used as a model succinctly to capture these feasible combinations. $J_{\rm M}$ is defined as a binary matrix of size $\sigma(P_\mu)\times\sigma(M)$ where element $J_{\rm M}(j,k) \in \{0,1\}$ is equal to one when event $e_{\mu_j m_k}$ exists. More formally, the existence of a principal function $t_{\mu_{j\pi}}$ in the state machine of machine m_k determines the value of the corresponding element of the transformation knowledge base

$$J_{\rm M}(j,k) = \begin{cases} 1 & \text{if } t_{\mu_{j\pi}} \in N_{m_k} \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

Next, a number of discrete holonomic constraints of the form

$$\bigcup_{i}^{n_k} K_i(E_{\mu m}) = \emptyset \tag{15}$$

are specified. These constraints are said to be scleronomic as they act purely on the event set and are independent of event sequence. Such constraints can arise from any phenomenon that reduces the capabilities of a production system e.g. tool wear or machine breakdowns. The description of the discrete holonomic constraints can be captured succinctly in a single binary matrix $K_{\rm M}$ of size $\sigma(P_\mu)\times\sigma(M)$ whose elements $K_{\rm M}(j,k) \in \{0,1\}$ are equal to one when a constraint eliminates event $e_{\mu_j m_k}$ from the event set. Intuitively, a constraint exists if any of the functions of the transformation process are not contained within the state machine of the corresponding machine

$$K_{\mathrm{M}}(j,k) = \begin{cases} 0 & \text{if } p_{\mu_j} \subseteq N_{m_k} \\ 1 & \text{otherwise} \end{cases} \tag{16}$$

In the case that the system uses centralized controllers (e.g. PLCs, centralized schedulers/dispatchers), this condition must be relaxed. First, a binary aggregation matrix A_{M} is reintroduced. In this context, it has size $\sigma(M) \times \sigma(R)$ and adapts equation 11 to

$$P_\mu = J_{\mathrm{M}} \odot (A_{\mathrm{M}} \circledast R) \tag{17}$$

This implies that a constraint on event $e_{\mu_j m_k}$ exists if any of the functions of the transformation process p_{μ_j} are not contained in the combined nets of the transformation machines and the associated secondary resources. This combined net N is given by

$$N = \bigcup_{\kappa}^{\sigma(R)} A_{\mathrm{M}}(k,\kappa) \odot N_{r_\kappa} \tag{18}$$

By definition of the aggregation operation $\circledast$, it follows that

$$K_{\mathrm{M}}(j,k) = \begin{cases} 0 & \text{if } p_{\mu_j} \subseteq (\lambda_k^T A_{\mathrm{M}}) N_{\mathrm{R}} \\ 1 & \text{otherwise} \end{cases} \tag{19}$$

where λ_k is the kth elementary column vector and N_{R} is the set of resource nets.

From this, the number of transformation degree of freedom can be found. They are defined as follows.

Definition 4.1. Transformation degrees of freedom: the set of independent transformation events $\mathcal{E}_M$ that completely define the available transformation processes in a production system.

Intuitively, they measure the number of ways that all the available transformation processes may be executed. Their number is given by

$$DOF_{\mathrm{M}} = \sigma(\mathcal{E}_{\mathrm{M}}) = \sum_j^{\sigma(P_\mu)} \sum_k^{\sigma(M)} [J_{\mathrm{M}} \ominus K_{\mathrm{M}}](j,k) \tag{20}$$

4.2 Transportation degrees of freedom

The method of developing transportation degrees of freedom is identical to its transformational counterpart. Only the system inputs change. Instead of using only the value-adding machines, a production system's transportation and storage activities can be completed by any of the primary resources $R_I = M \cup B \cup H$. Furthermore, instead of a set of transformation processes, a set of transportation processes P_η are established. By definition, there are $\sigma^2(B_{\mathrm{S}})$ such processes. Of these, $\sigma(B_{\mathrm{S}})$ are 'null' (i.e. storage) processes. For simplicity, the set of buffers and primary resources are assumed to be partially ordered such that $B = \{b_{s[\sigma(\mathrm{M})+1]}, \cdots, b_{s[\sigma(\mathrm{M})+\sigma(\mathrm{B})]}\}$ and $H = \{r_{[\sigma(B_{\mathrm{S}})+1]}, \cdots, r_{[\sigma(B_{\mathrm{S}})+\sigma(\mathrm{H})]}\}$. This allows the convention that transportation process $p_{\eta u}$ transport products from buffer b_{sy_1} to b_{sy_2} such that $u = \sigma(B_{\mathrm{S}})(y_1 - 1) + y_2$. This restriction on the relationship of indices between (y_1, y_2) and u in this definition plays a prominent role in later stages in the development of manufacturing degrees of freedom. Most notably, the relationship $u = \sigma(B_{\mathrm{S}})(y_1 - 1) + y_2$ implies that u equals the sequence of digits $((y_1 - 1), y_2)$ in base $\sigma(B_{\mathrm{S}})$. This straightforwardly yields two useful results: $y_1 = (u-1)/\sigma(B_{\mathrm{S}}) + 1$ where '/' represents integer division, and $y_2 = mod[(u-1), \sigma(B_{\mathrm{S}})] + 1$, where mod$(x, y)$ represents the modulus of x with respect to y.

Following the same method described in the previous section yields the number of transportation degrees of freedom.

Definition 4.2. Transportation degrees of freedom: the set of independent transportation events $\mathcal{E}_{\mathrm{H}}$ that completely define the available transportation processes in a production system

$$DOF_{\mathrm{H}} = \sigma(\mathcal{E}_{\mathrm{H}}) = \sum_u^{\sigma(P_\eta)} \sum_v^{\sigma(R_I)} [J_{\mathrm{H}} \ominus K_{\mathrm{H}}](u,v) \tag{21}$$

Equation (21), expresses the total number of transportation degrees of freedom, including those associated with null transportation processes. To calculate the non-null degrees of freedom, equation (21) becomes

$$DOF_{\mathrm{H1}} = \sigma(\mathcal{E}_{\mathrm{H1}}) = \sum_u^{\sigma(P_\eta)} \sum_{v=[\sigma(B_{\mathrm{S}})+1]}^{\sigma(R_I)} [J_{\mathrm{H}} \ominus K_{\mathrm{H}}](u,v) \tag{22}$$

4.3 Scleronomic production degrees of freedom

At times, it is preferable to view a manufacturing system as a whole rather than its transformational and transportation parts. Hence, the two types of degree of freedom may be treated together, as they were for mechanical systems. The production system event set, production process event set, production system knowledge base, and the production system constraints matrix become

$$E = E_{\mu m} \cup E_{\eta r} \tag{23}$$

$$P = P_\mu \cup P_\eta \tag{24}$$

$$J_{\mathrm{S}} = \left[\begin{array}{c|c} J_{\mathrm{M}} & 0 \\ \hline \leftarrow \quad J_{\mathrm{H}} & \rightarrow \end{array} \right] \tag{25}$$

$$K_{\mathrm{S}} = \left[\begin{array}{c|c} K_{\mathrm{M}} & 1 \\ \hline \leftarrow \quad K_{\mathrm{H}} & \rightarrow \end{array} \right] \tag{26}$$

respectively. It follows that the scleronomic production degrees of freedom is defined as follows.

Definition 4.3. Production degrees of freedom: the set of independent production events $\mathcal{E}$ that completely define the available production process in a production system.

Their number is given by

$$DOF_S = \sigma(\mathcal{E}) = \sum_{w}^{\sigma(P)} \sum_{v}^{\sigma(R_I)} [J_S \ominus K_S](w, v) \tag{27}$$

While aggregating transformation and transportation degrees of freedom is mathematically straightforward, such a measure may mask the intrinsic differences in importance of value-adding and transportation activities. Nevertheless, from a reconfiguration point of view, both process types may be equally important to achieve the full production of a product.

4.4 Rheonomic production degrees of freedom

The previous three sub-sections introduced production degree of freedom as independent. Intuitively, it is known, however, that transformation and transportation processes must alternate so that a product can be manufactured progressively from one resource to another. This phenomenon has its mechanical equivalent. In mechanical systems, two links are connected by a joint that constrains the motion of both links by introducing dependencies between the coordinates of the multi-body system. Similarly, a production system has constraints that introduce dependencies in the sequence of events. This section shifts away from the scleronomic sub-branch in Fig. 2 in order to develop rheonomic production degrees of freedom in a manner similar to the previous developments. Ultimately, this measure provides a sequence-dependent measure of the capabilities in a manufacturing system.

Unlike scleronomic production degrees of freedom, rheonomic production degrees of freedom are concerned with the substrings of a production system (language), as opposed to just its events.

Definition 4.4. Rheonomic production degrees of freedom: the set of independent production strings $\mathcal{Z}$ that completely describe the production system language.

In other words, the production system language $\mathcal{L}$ can be described equally well in terms of the Kleene closure of the scleronomic and rheonomic production degrees of freedom

$$\mathcal{L} = \mathcal{E}^* = \mathcal{Z}^* \tag{28}$$

That said, there exists an infinite number of strings $z \in \mathcal{Z}$ that are subsets of the production system language. For mathematical tractability, the length of strings z are limited to two. Strings of longer length are discussed elsewhere [**5**].

In the calculation of scleronomic production degrees of freedom, the size of the event set was calculated, and then a number of constraints was found. Their difference resulted in the number of scleronomic production degrees of freedom. The development proceeds similarly here. Given string $z_{\varrho\psi} = e_{w_1 v_1} e_{w_2 v_2} \in Z$ where $\varrho = \sigma(P)(w_1 - 1) + w_2$ and $\psi = \sigma(R)(v_1 - 1) + v_2 \forall w_1, w_2 \in \{1, \sigma(P)\}$ and $\forall v_1, v_2 \in \{1, \sigma\ (R_I)\}$. These feasible strings can be captured succinctly in a single binary matrix J_ρ of size $\sigma^2(P) \times \sigma^2(R_I)$ whose elements $J_\rho(\varrho, \psi) \in \{0, 1\}$ are equal to one when string $z_{\varrho\psi}$ exists and can be calculated as

$$J_\rho = J_S \otimes J_S \tag{29}$$

where $\otimes$ is the Kronecker tensor product.

As before, a binary constraints matrix K_ρ of size $\sigma^2(P) \times \sigma^2(R)$ is used to describe the potential elimination of strings $z_{\varrho\psi} = e_{w_1 v_1} e_{w_2 v_2}$ from the production system string set.

The conditions for these constraints can also be quantified. In order for one degree of freedom to follow another, the outputs of the former must be

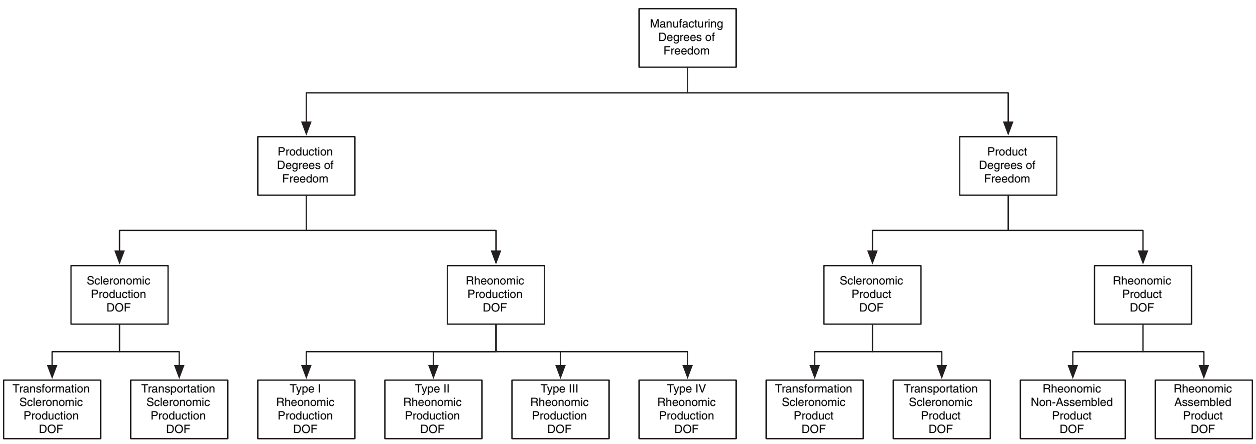


Fig. 2 Taxonomy of manufacturing degrees of freedom

Table 2 Summary of rheonomic production degrees of freedom

Type	Perpetual constraint	Calculation	Number of constraints	DOF_ρ
I	$k_1 = k_2$	$\sum_{\varphi}^{\sigma^2(P_\mu)} \sum_{\beta}^{\sigma^2(M)} [J_{MM\rho} \ominus K_{MM\rho}](\varphi, \beta)$	$\sigma^2(P_\mu)[\sigma(M) - 1]$	$\sigma^2(P_\mu)\sigma(M)$
II	$k_1 - 1 = \frac{(u_1-1)}{\sigma(B_S)}$	$\sum_{\zeta}^{\sigma(P_\mu)\sigma(P_\eta)} \sum_{\delta}^{\sigma(M)\sigma(R)} [J_{MH\rho} \ominus K_{MH\rho}](\zeta, \delta)$	$\sigma^2(P\mu)\sigma(M)\sigma(R) \cdot\sigma(B_S)[\sigma(B_S) - 1]$	$\sigma(P\mu)\sigma(M) \cdot \sigma(R)\sigma(B_S)$
III	$k_1 - 1 = \|[(u_1 - 1), \backslash\sigma(B_S)]$	$\sum_{\vartheta}^{\sigma(P_\mu)\sigma(P_\eta)} \sum_{\theta}^{\sigma(M)\sigma(R)} [J_{HM\rho} \ominus K_{HM\rho}](\vartheta, \theta)$	$\sigma^2(P\mu)\sigma(M)\sigma(R) \cdot\sigma(B_S)[\sigma(B_S) - 1]$	$\sigma(P_\mu)\sigma(M) \cdot \sigma(R)\sigma B_S$
IV	$\|[(u_{-1} - 1), \backslash\sigma(B_S)] = \frac{(u_2-1)}{\sigma(B_S)}$	$\sum_{\upsilon}^{s^2(P_\eta)} \sum_{\psi}^{s^2(R)} [J_{HH\rho} \ominus K_{HH\rho}](\upsilon, \psi)$	$\sigma^2(R)\sigma^3(B_S) \cdot [\sigma(B_S) - 1]$	$\sigma^2(R)\sigma^3(B_S)$

equivalent to the inputs of the latter. Within the formalism of Petri nets, the set of outputs or exit places of a process p_{w_1} is given by

$$S_{w_1x} = \{s \in S_{w_1} | s^\bullet = \emptyset\} \tag{30}$$

Similarly, the set of inputs or entry places of a process p_{w_2} is given by

$$S_{w_2e} = \{s \in S_{w_2} | {}^\bullet s = \emptyset\} \tag{31}$$

In order for a functional interface to occur, these input and output places must be equivalent and also be a part of the state machines of both the first and second resources. Formally, given string $e_{w_1v_1}e_{w_2v_2}$

$$K_\rho(\varrho, \psi) = \begin{cases} 0 & \text{if } S_{w_1x} = S_{w_2e} \subseteq (N_{r_{v_1}} \cap N_{r_{v_2}}) \\ 1 & \text{otherwise} \end{cases} \tag{32}$$

In the case of centralized controllers, this condition is relaxed to

$$K_\rho(\varrho, \psi) = \begin{cases} 0 & \text{if } S_{w_1x} = S_{w_2e} \subseteq (\lambda_{v_1}^T A \circledast N_R \cap \lambda_{v_2}^T A \circledast N_R) \\ 1 & \text{otherwise} \end{cases} \tag{33}$$

It follows that the number of rheonomic production degrees of freedom is

$$DOF_\rho = \sigma(\mathcal{Z}) = \sum_{\varrho}^{\sigma^2(P)} \sum_{\psi}^{\sigma^2(R_I)} [J_\rho \ominus K_\rho](\varrho, \psi) \tag{34}$$

Rheonomic production degrees of freedom can be classified in a manner similar to the one used for scleronomic production degrees of freedom. This time, the two classes are combined into pairs. As a result, there are four types of rheonomic production degree of freedom as follows.

1. Type I ($DOF_{MM\rho}$): $e_{\mu_{j_1}m_{k_1}} e_{\mu_{j_2}m_{k_2}}$ – two successive transformations
2. Type II ($DOF_{MH\rho}$): $e_{\mu_{j_1}m_{k_1}} e_{\eta_{u_1}r_{Iv_1}}$ – transformation, transportation
3. Type III ($DOF_{HM\rho}$): $e_{\eta_{u_1}r_{Iv_1}} e_{\mu_{j_1}m_{k_1}}$ – transportation, transformation
4. Type IV ($DOF_{HH\rho}$): $e_{\eta_{u_1}r_{Iv_1}} e_{\eta_{u_1}r_{Iv_2}}$ – two successive transportations

All four classes have perpetually existing constraints that set an upper bound on a maximally free production system. For Type I, two successive transformation events must both occur at the same machine; $k_1 = k_2$. For Type II, when a transportation event follows a transformation event, the transportation event must begin at the machine at which the transformation process was first realized. As a result, the constraint $k_1 = (u_1 - 1)/\sigma(B_S) + 1$ always applies. The exact functional form of this constraint is solved from the relationship of indices found in the definition of transportation processes. Similarly, Type III degrees of freedom require that the transportation event ends at the machine at which the subsequent transformation is realized; $k_1 = \text{mod}[(u_1 - 1), \sigma(B_S)] + 1$. Finally, for Type IV, two successive transportation events must meet at the same intermediary location; $\text{mod}[(u_1 - 1), \sigma(B_S)] = (u_2 - 1)/\sigma(B_S)$. Table 2 summarizes these constraints and then uses the appropriate calculation to find the associated number of rheonomic production degrees of freedom.

4.5 Causes for loss of production degrees of freedom

These measures can now be used to shed light on some of the causes for the loss of production degrees of freedom. Generally, the loss of production degrees of freedom comes about by disabling a given production process on a given resource. Imagine two classes of constraint: one that affects the set of resources, and the other that affects individual production processes. For the first class, the breakdown of a resource applies a set of constraints, one for each of its production processes. For the second class, the nature of an arbitrary production process must be considered. A production process is realized when a set of subfunctions are completed in a specific parallel and serial arrangement. The disabling of any of these subfunctions disturbs the arrangement and disables the entire production process.

4.5.1 *Inflexible tooling and fixturing*

Inflexible tooling and fixturing can disable certain production processes in exactly this way. In the case of tooling, a given machine may have more than one tool to realize a set of transformation processes. An flexible manufacturing system may realize more transformation processes than a mill, which, in turn, realizes more than a drill press. Additionally, a given tool, as compared to another, may be able to realize more transformation processes because the former is better able to address a wide variety of physical constraints, such as material size/geometry, stiffness/hardness, and tolerance. This suggests that machines that can modularize their cache of tools can flexibly add or remove from the system's transformation degrees of freedom. This practice is in fact common in job-shop machining centres where a wide variety of products require a similarly diverse set of transformation processes.

Similarly, the fixturing on a given machine, or end-effector on a given material handler, may radically affect its ability to realize production processes. Two production processes can be identical in every regard except that they require different fixtures to accommodate radically different product geometries. Much like with tooling, this suggests that flexible fixturing can potentially increase the system's production degrees of freedom.

4.5.2 *Rigid execution control*

The system's execution control can also be viewed as a subfunction of the transformation and transportation processes. It acts as a supervisory controller which rejects strings from the manufacturing system language. This can be in the form of scleronomic constraints which act directly on the event set. Realistically, this may occur if each tool and/or fixture does not have its associated execution program. Alternatively, the controller can impose rheonomic constraints by rejecting whole strings. This may occur if a centralized execution controller has a single monolithic control program that combines the execution code of a number of production processes. For example, code that pushes products without choice down an automation line can easily be conceived. In this case, the resulting manufacturing system language would be $\mathcal{L} = e_{\mu_1 m_1} e_{\eta_2 r_6} e_{\mu_2 m_2} e_{\eta_5 r_6} e_{\mu_3 m_3}$ when it could have been written to support the language $\mathcal{L} = (e_{\eta_u r_v} e_{\mu_j m_k})^*$. Moreover, such a monolithic program would have to be significantly rewritten in the face of any addition, removal, or rearrangement of production resources and their associated processes.

4.5.3 *Rigid scheduling*

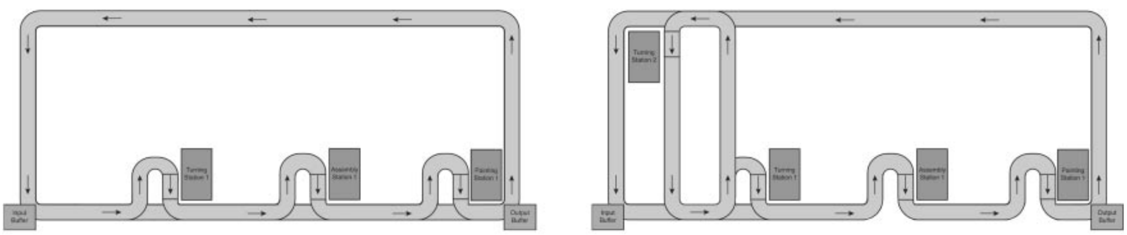
Rigid scheduling imposes both scleronomic and rheonomic constraints similarly. Over the scheduled period, it may be defined that only a given resource will realize a given production process for a particular product. This may be particularly limiting in the event of a resource breakdown. A reactive schedule would allow for such products to be rerouted to available redundant resources.

4.5.4 *Rigid technical planning*

Rigid or 'incomplete' technical planning imposes scleronomic constraints. Often, a product or its associated production processes are planned for the 'best' resource; the resource that realizes the production process with highest quality in the fastest time. Most process plans found in industry only state one machine type for each process; there may exist other resources capable of realizing the production process, albeit at reduced but acceptable speed or quality.

5 AN ILLUSTRATIVE EXAMPLE

To demonstrate the application of the production degrees of freedom measures, the hypothetical 'Starling' automated manufacturing system is taken as an illustrative example. This system produces customized bird-feeders from cylindrical wooden components that need to be turned for slots and tabs, milled, assembled, and painted in one of three colours. They are transported between value-adding resources and two independent buffers on three shuttles. The initial configuration of the plant is shown in Fig. 3(a), while Fig. 3(b) shows it after the



(a) Stage I (b) Stage II

Fig. 3 Starling manufacturing system

Table 3 Starling manufacturing system degrees of freedom variables

	Stage I	Stage II
M	{Turning station 1, Assembly station 1, Painting station 1}	{Turning station 1, Assembly station 1, Painting station 1, Turning station 2}
B	{Input buffer, Output buffer}	{Input buffer, Output buffer}
H	{Shuttle 1, Shuttle 2, Shuttle 3}	{Shuttle 1, Shuttle 2, Shuttle 3}
P_M	{Lathe tab, Lathe slot, Mill hole, Assemble, Paint red, Paint yellow, Paint green}	{Lathe tab, Lathe slot, Mill hole, Assemble, Paint red, Paint yellow, Paint green}
P_η	$\left\{\begin{array}{c} m_1m_1, m_1m_2, m_1m_3, m_1b_1, m_1b_2, \\ m_2m_1, m_2m_2, m_2m_3, m_2b_1, m_2b_2, \\ m_3m_1, m_3m_2, m_3m_3, m_3b_1, m_3b_2, \\ b_1m_1, b_1m_2, b_1m_3, b_1b_1, b_1b_2, \\ b_2m_1, b_2m_2, b_2m_3, b_2b_1, b_2b_2 \end{array}\right\}$	$\left\{\begin{array}{c} m_1m_1, m_1m_2, m_1m_3, m_1m_4, m_1b_1, m_1b_2, \\ m_2m_1, m_2m_2, m_2m_3, m_2m_4, m_2b_1, m_2b_2, \\ m_3m_1, m_3m_2, m_3m_3, m_3m_4, m_3b_1, m_3b_2, \\ m_4m_1, m_4m_2, m_4m_3, m_4m_4, m_4b_1, m_4b_2, \\ b_1m_1, b_1m_2, b_1m_3, m_2m_4, b_1b_1, b_1b_2, \\ b_2m_1, b_2m_2, b_2m_3, b_2m_4, b_2b_1, b_2b_2 \end{array}\right\}$

addition of a second turning station. While this reconfiguration added greater turning capacity, it caused frequent faults at the assembly station owing to a higher duty cycle.

Table 3 summarizes the measurement process and its results. The notation m_xm_y denotes a transportation process between pairs of machines m_x and m_y. The associated knowledge bases (given in the Appendix) arise straightforwardly, giving the four scleronomic degrees of freedom measurements presented in Table 4. Initially, the system had seven transformation degrees of freedom between the seven transformation processes and the three value-adding machines. The addition of the second turning centre added three new degrees of freedom. However, the frequent faults of the assembly machine imposed a constraint on the single assembly degrees of freedom. The addition of the turning centre also greatly expanded the size of the transportation system knowledge base. This potential was utilized when the track systems were modified so that loading stations did not block part flow. As a result, transportation processes such as m_4m_2 became enabled. Furthermore, the addition of the turning station loop opened the possibility for automated rework with processes such as b_2m_4. As a result, the system added 19 new transportation degrees of freedom.

Table 5 summarizes the rheonomic production degrees of freedom measurements. In Stage I, the 19

Table 4 Starling manufacturing system scleronomic production degrees of freedom

	Stage I	Stage II
DOF_M	7	9
DOF_H	20	39
DOF_{H1}	15	33
DOF_S	27	48

Table 5 Starling manufacturing system rheonomic production degrees of freedom

	Stage I	Stage II
$DOF_{MM\rho}$	19	28
$DOF_{MH\rho}$	28	67
$DOF_{HM\rho}$	28	64
$DOF_{HH\rho}$	80	252
DOF_ρ	155	411

Type I degrees of freedom may be interpreted as a sum of three groups, 3(3)+3(3)+1(1). Whereas the turning and painting stations allow three transformation process to be followed by another three, the assembly machine has only one way to execute two consecutive processes. The 28 Type II degrees of freedom may be interpreted as [1(3)+1(1)+1(3)](1+3). The three value-adding machines can realize 3, 1, and 3 transformation processes, respectively, followed by four options: storage at the same

Table 6 Variations between production degree of freedom measures

Measures	Processes	Resources	Knowledge base	Constraints matrix
DOF_{M}	P_{μ}	M	J_{M}	K_{M}
DOF_{H}	P_{η}	R_{I}	J_{H}	K_{H}
DOF_{S}	P	R_{I}	J_{S}	K_{S}
$DOF_{\mathrm{MM}\rho}$	$P_{\mu}P_{\mu}$	$M\&M$	$J_{\mathrm{MM}\rho}$	$K_{\mathrm{MM}\rho}$
$DOF_{\mathrm{MH}\rho}$	$P_{\mu}P_{\eta}$	$M\&R_{\mathrm{I}}$	$J_{\mathrm{MH}\rho}$	$K_{\mathrm{MH}\rho}$
$DOF_{\mathrm{HM}\rho}$	$P_{\eta}P_{\mu}$	$R_{\mathrm{I}}\&M$	$J_{\mathrm{HM}\rho}$	$K_{\mathrm{HM}\rho}$
$DOF_{\mathrm{HH}\rho}$	$P_{\eta}P_{\eta}$	$R_{\mathrm{I}}\&R_{\mathrm{I}}$	$J_{\mathrm{HH}\rho}$	$K_{\mathrm{HH}\rho}$
DOF_{ρ}	PP	$R_{\mathrm{I}}\&R_{\mathrm{I}}$	J_{ρ}	K_{ρ}

machine or movement by three shuttles. The Type III degrees of freedom are equivalent by symmetry. The 80 Type IV degrees of freedom may be interpreted as (5)(4)(4). For each of the five buffers where a Type IV rheonomic degree of freedom can meet, four resources (i.e. three shuttles and a buffer) can bring the part to the buffer and four more can move it away. Intuitive explanation of Stage II is difficult, but it should be noted that the addition of a single resource in this caused a 165 per cent increase in the number of rheonomic degree of freedom.

Such measurements may be practically applied as part of an iterative design loop that facilitates systematic and incremental reconfigurability improvements in a manufacturing system. Because the measurements depend functionally on the system's design variables, these variables can be modified so as to fill the system knowledge bases and eliminate constraints. For example, modular tool caches or fixtures can significantly fill the knowledge bases. Alternatively, the constraint matrices can identify in which manufacturing control system levels scleronomic or rheonomic constraints may be appearing. Given this 'diagnostic' type of information, the system integrator can act during the design or reconfiguration phases to improve the system's reconfigurability.

6 CONCLUSIONS AND FUTURE WORK

In the last four sections, eight different production degrees of freedom measures were developed as variations on the theme of three common elements. Capabilities were described in terms of discrete events that were captured in axiomatic design knowledge bases. Next, a same-sized constraints matrix was used to describe any constraints on those capabilities. Finally, a 'Boolean difference' of the two matrices resulted in the measure. Table 6 summarizes the measures.

The need for these variations, shown originally in Fig. 2, arises from two specific characteristics of manufacturing systems. First, transformation and transportation activities have intrinsically different values in manufacturing and, therefore, have to be distinguished. Next, products impose particular sequences of production. Therefore, manufacturing system capabilities need to be considered not just as a loose collection of transformations and transportations, but also as integrated sequences. These two differences account for the six elemental production degrees of freedom types and their two combinations.

The production degree of freedom measures provide a quantitative description of 'reconfiguration potential' because they describe a system's capabilities and how they can be changed. Generally speaking, a reconfiguration process can be classified as changes in the production resources, their processes or their combinations. Mathematically, production degrees of freedom would describe such a reconfiguration as

$$(J_{\mathrm{S}}, K_{\mathrm{S}}, K_{\rho}) \rightarrow (J'_{\mathrm{S}}, K'_{\mathrm{S}}, K'_{\rho}) \quad (35)$$

The development of production degrees of freedom opens up many possible directions for future work. First, they form an integral part of a systematic approach to reconfigurability measurement described elsewhere [**5**]. Specifically, these measures gain greater meaning when compared to product degree of freedom measures that assess the product-dependent aspects of a system's reconfiguration potential. In such a way, the entirety of the taxonomy shown in Fig. 2 can be addressed. Furthermore, in addition to 'reconfiguration potential' measurement, a holistic view of reconfigurability measurement process must address 'reconfiguration ease' [**1–4**].

These measures have the potential to affect future work in the greater manufacturing research community. Such a need has already been identified in supply networks [**73**] but could also be applied in continuous/batch manufacturing systems [**74**] where incremental change is necessary. Application into these multiple contexts may be facilitated by the generic nature of production degrees of freedom. Finally, these measures may be integrated into IT-based support tools that may improve the manufacturing system design methodologies.

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APPENDIX

Table 7 Starling manufacturing system transportation degrees of freedom

	Stage I	Stage II
J_M	$\begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
K_M	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$
J_H	see Stage I table below	see Stage II matrix below

J_H, Stage I:

	Turning station	Assembly station	Painting station	Input buffer	Output buffer	Shuttle 1	Shuttle 2	Shuttle 3
m_1m_1	1	0	0	0	0	0	0	0
m_1m_2	0	0	0	0	0	1	1	1
m_1m_3	0	0	0	0	0	0	0	0
m_1b_1	0	0	0	0	0	0	0	0
m_1b_2	0	0	0	0	0	0	0	0
m_2m_1	0	0	0	0	0	0	0	0
m_2m_2	0	1	0	0	0	0	0	0
m_2m_3	0	0	0	0	0	1	1	1
m_2b_1	0	0	0	0	0	0	0	0
m_2b_2	0	0	0	0	0	0	0	0
m_3m_1	0	0	0	0	0	0	0	0
m_3m_2	0	0	0	0	0	0	0	0
m_3m_3	0	0	1	0	0	0	0	0
m_3b_1	0	0	0	0	0	1	1	1
m_3b_2	0	0	0	0	0	0	0	0
b_1m_1	0	0	0	0	0	1	1	1
b_1m_2	0	0	0	0	0	0	0	0
b_1m_3	0	0	0	0	0	0	0	0
b_1b_1	0	0	0	1	0	0	0	0
b_1b_2	0	0	0	0	0	0	0	0
b_2m_1	0	0	0	0	0	0	0	0
b_2m_2	0	0	0	0	0	0	0	0
b_2m_3	0	0	0	0	0	0	0	0
b_2b_1	0	0	0	0	0	1	1	1
b_2b_2	0	0	0	0	1	0	0	0

J_H, Stage II:

$$\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0
\end{bmatrix}$$