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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 multiagent 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 second of two in this issue to address reconfigurability measurement. Specifically, 'reconfiguration ease' has often been qualitatively argued to depend on the system's modularity. For this purpose, this paper develops modularity measures in a three-step approach. Firstly, the nature of typical manufacturing system interfaces is discussed. Next, the qualitative understanding underlying existing modularity measures is distilled. Finally, these understandings are synthesized for a manufacturing system context. This approach forms the second of two pillars that together lay the foundation for an integrated reconfigurability measurement process described elsewhere.

Keywords: reconfigurable manufacturing systems, holonic manufacturing systems, multiagent systems, modularity, reconfigurability, reconfigurability measurement

1 INTRODUCTION

In the 1990s the global marketplace has necessitated the production of mass-customized products of increasingly short product life cycle [**1**, **2**]. These dual requirements have necessitated that enterprises find ways quickly and incrementally to adjust production capacity and capability. In other words, as the continually growing variety of products are introduced, ramped up, phased out, and finally made obsolete, the capabilities of production resources must be reallocated to the product variants that need them most. To fulfil these needs, the concept of reconfigurable manufacturing systems has been proposed as a set of possible solutions.

Definition 1: reconfigurable manufacturing system

'[A system] designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements [**3**].'

Over the last decade, many technologies and design approaches have been developed to enable reconfigurability in manufacturing systems [**4**, **5**]. These have included modular machine tools [**6**], distributed automation [**7**, **8**], multiagent systems [**9**, **10**], and holonic manufacturing systems [**11–13**]. While initial efforts to assess these design approaches have been reported [**14–17**], numerous authors have identified the need for a holistic reconfigurability measurement process [**18–24**]. Hence, it remains inconclusive whether the resulting designs achieve their intended level of reconfigurability. This paper is the second of two in this issue that propose elements of an integrated reconfigurability measurement process based upon the complementary principles of reconfiguration potential [**23**, **25–27**] and reconfiguration ease [**23**, **28–31**]. The latter of these has already been qualitatively argued to depend on the system's modularity [3, 32]. Hence, this paper seeks to address reconfiguration ease by developing a new set of quantitative manufacturing modularity measures.

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

Definition 1: reconfigurability [23, 31]

The ability to add, remove, and/or rearrange in a timely and cost-effective manner the components and functions of a system, which can result in a desired set of alternate configurations.

Furthermore, the research scope is restricted to two classes of reconfigurations:

(a) changes in the number and type of production resources and
(b) changes in the number and type of product variants.

2 BACKGROUND

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

2.1 Measurement processes

Generally speaking, a measurement process requires:

1. Identification of measurables
2. Methods for measuring the measurables
3. Models for describing/modelling the system
4. Identification of structure-dependent properties
5. Formulaic measures of relating those models to those properties

The requirements can be graphically represented as a sequential data flow diagram in Fig. 1. Implicitly, as an objective, a set of measured properties need to be identified. In most measurement processes, these properties are distinct from the system measurables 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 [34]. This requires that the measurables be related using a set of models. Finally, the mathematical theory of measurement [35] requires a set of measures. These measures are a specific class of mathematical functions and serve to convert related measurables to the final measured property [36].

Fig. 1 A generic measurement process

2.2 Design structure matrix

One model often used in the measurement of system modularity is the design structure matrix (DSM). It is a systems analysis tool that captures the interactions, interdependencies, and interfaces between components of a complex system in a compact and clear representation [37]. Given two components A and B, they may interact in a parallel, sequential, or coupled fashion. These interactions may be spatial, structural, energy, material, or information interfaces [38]. Figure 2 shows the graphical representation of these interactions and their associated design structure matrices. Essentially, off-diagonal elements reflect interaction. The placement of an off-diagonal 'X' represents the existence of an interaction between two components A and B [37]. Some authors, however, have replaced the 'X' with numerical values in order to assess the strength of a particular interaction subjectively [39, 40]. The DSM is formally described in reference [41] and a comprehensive tutorial with accompanying application can be found in references [23] and [37].

The design structure matrix has already been applied in numerous works, which indicate its applicability to the study of reconfigurability in manufacturing systems. Its application to automotive climate control systems [39] and large commerical aircraft engines [38] allows an analogy to be drawn between the cross-energy domain transportive and transforming functions of an aircraft engine to those of manufacturing systems. It has also been used to facilitate

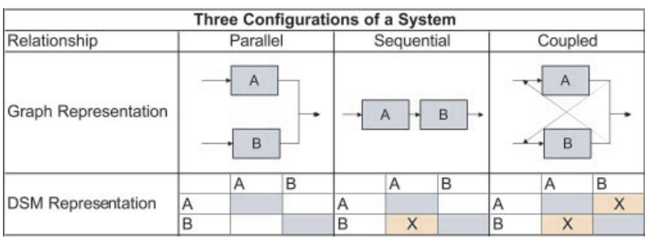


Fig. 2 DSM representations of system configurations [37]

the realization of highly customized products [**42**] and their platforms [**43**]. A reconfigurable manufacturing system, in a sense, is a system that undergoes customization over time much like a customized product line. Finally, the model has found application in product life cycle engineering [**40**, **44**] and hence may play a role in the efficient maintenance and decommissioning of manufacturing systems.

2.3 Production design structure matrix

Most recently, the production design structure matrix has been developed as a DSM specific to production. Its method of application and case studies are described elsewhere [**23**, **27**, **29–31**] and only its essential elements are described here. To begin, the inherently open manufacturing system must be translated to an analogous closed one. Manufacturing systems composed of four types of resources R (value-adding machines M, material handlers H, independent buffers B, and centralized controllers Q) convert information, energy, and material into other forms. Furthermore, the product line L is included as an intrinsic part of the analogous closed system. Depending on the application, these products may adhere to the intelligent product paradigm [**45**]. Additionally, the system boundary acts as an infinite source of the necessary system inputs and an infinite sink to the generated outputs. The system boundary also serves as a common platform to which all the manufacturing system components can connect. For example, basic factory services such as power and networking are included as part of the system boundary. Interactions between two manufacturing system components via the system boundary are treated as direct. Given these subsystems, Fig. 3(a) shows the production DSM of a distributed manufacturing with one of each type of production resource, while Fig. 3(b) adds a centralized controller to the subsystems list.

These subsystems can then be decomposed into constituent components using an interface-based method of stepwise refinement [**23**, **31**]. In order to systematize the first iteration of this stepwise method, typical components can be identified for each of the previously defined subsystems.

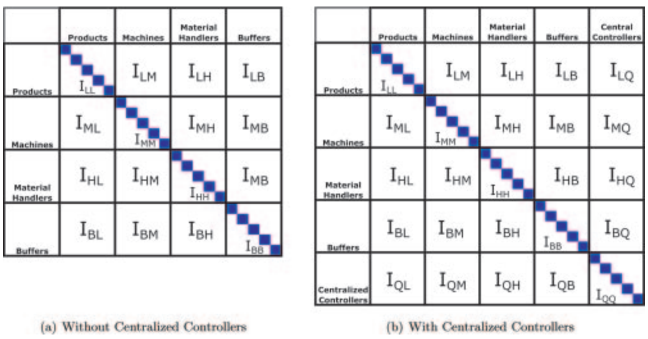


Fig. 3 Production system design structure matrix

2.3.1 *Transforming machine components*

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

$$C_{\mathrm{m}} = \{\text{location}, \text{tool(s)}, \text{fixture(s)}, \text{controllers}\} \quad (1)$$

2.3.2 *Material handling components*

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

$$C_{\mathrm{h}} = \{\text{motion region, motion mechanism,}\ \text{end-effectors(s), controllers}\} \quad (2)$$

2.3.3 *Independent buffer components*

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

$$C_{\mathrm{b}} = \{\text{location}, \text{fixture(s)}, \text{controllers}\} \quad (3)$$

2.3.4 *Centralized controller components*

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

$$C_q = \left\{ \begin{array}{l} \text{transformation execution controller,} \\ \text{transportation execution controller,} \\ \text{transformation scheduling and} \\ \quad \text{planning controller,} \\ \text{transportation scheduling and} \\ \quad \text{planning controller} \end{array} \right\} \tag{4}$$

2.3.5 *Product components*

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

$$C_l = \{\text{parts/features, intelligent software(s)}\} \tag{5}$$

Once the subsystem component lists have been identified, the interfaces between them can be captured into the production DSM. For this purpose, CAD/CAM data, process plans, UML diagrams can all be included [**23**, **29–31**]. High-level interfaces can be identified first and then characterized in increasing detail as the component lists are decomposed further in a stepwise fashion [**23**, **31**]. More prescriptive methods for constructing the DSM are the subject of ongoing research [**23**, **31**, **77**]

2.4 Limitations of existing measures for manufacturing systems

The next step in a modularity measurement process requires a modularity measure that draws upon the production DSM. Unfortunately, according to the most recent modularity literature review, there is no consensus on the property's definition, and in one experiment results showed no statistical significance in the modularity ranking that a group of product-design graduate students assigned to a group of products [**46**]. Clearly, developing a rational or absolute scale [**47**] measure under these conditions would have a limited benefit because the underlying *intuitive* concept is not well understood. Stated another way, the *current* understanding of modularity does not fulfil the measurement axioms [**47**]. Despite these difficulties, the importance of modularity to system structure is clear and its impact on reconfigurability as the first and primary key characteristic [**48**] is well accepted. As a result, the author agrees with Gershenson *et al.* [**46**] that 'there is an obvious need for further research in product modularity'.

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

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

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

3 MANUFACTURING MODULARITY MEASURES

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

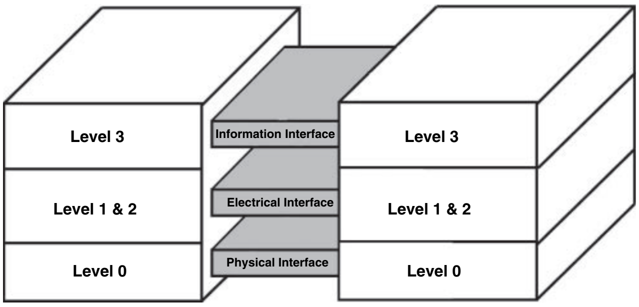


Fig. 4 Multilevel interfaces of production resources

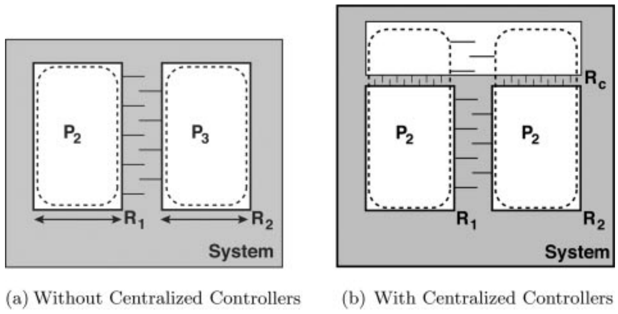


Fig. 5 Multiparametered resource interfaces

3.1 Manufacturing system interfaces

Throughout the literature, modularity is dependent on the complexity of the interface between two subsystems [**49**]. Hence, the typical complexity in manufacturing system interfaces needs to be better understood. The first complicating factor is that the nature of the interface changes dramatically at each of the levels of a manufacturing system [**3**]. Figure 4 shows some of the typical interfaces at the various levels of the production system. At the lowest level, the physical process occurs, often long a mechanical, thermal, or chemical interface. Higher up, the continuous real-time control layer typically has electrical interfaces such as time-varying voltage signals. In level 2, the discrete execution control interfaces are simultaneously electrical signals and binary information. Finally, at level 3, the interfaces are entirely information. Information interfaces transfer minimal amounts of energy but gain their importance by the meaning associated with the transfer. Each of these energy domains typically has its own modelling techniques associated with a specific engineering discipline.

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

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

(a) Type I: primary resource to primary resource
(b) Type II: primary resource to secondary resource
(c) Type III: intrasecondary resource interface

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

3.2 Understanding modularity qualitatively

These typical manufacturing system interfaces may be captured into a production DSM, but the measurement process would not be complete without a modularity measure. Given the insufficiency of the modularity measures presented in the literature, the discussion must return to the qualitative understanding of the property. The strategy for the redevelopment of the understanding consists of three elements:

(a) common and mutually agreeing understanding behind the presented modularity measures are incorporated;

(b) the DSM is imposed as a conceptual framework to organize these elements; and
(c) each understanding is presented in terms of a comparison scenario and described graphically with its associated pair of design structure matrices.

Before describing these comparison scenarios, it is important to note that any discussion of the DSM can be framed in terms of six variables. They are:

(a) total coupling (intersubsystem interaction) (a_o),
(b) total cohesion (intrasubsytem interaction) (a_d),
(c) total behaviour (a),
(d) total possible intersubsystem interaction ($\mathcal{V}_\text{o}$),
(e) total possible intrasubsystem interaction ($\mathcal{V}_\text{d}$), and
(f) total possible interaction ($\mathcal{V}$). These variables adhere to two constraints

$$\mathcal{V} = \mathcal{V}_\text{d} + \mathcal{V}_\text{o}$$
$$a = a_\text{d} + a_\text{o} \tag{6}$$

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

3.2.1 *Scenario I: greater coupling, ceteris paribus*

As a baseline scenario, if a system $\mathcal{S}_1$ has greater coupling than a system $\mathcal{S}_2$ of equal behaviour and equal number of subsystems and components, then $\mathcal{S}_2$ is more modular than $\mathcal{S}_1$ [**39**, **40**, **42**, **49**, **50–54**, **56–62**, **66–69**]. As seen in Fig. 6, $\mathcal{S}_1$ and $\mathcal{S}_2$ would have DSMs of the same size and density but $\mathcal{S}_1$ would have more of its interactions in the off-block diagonal regions.

3.2.2 *Scenario II: greater cohesion, ceteris paribus*

If a system $\mathcal{S}_1$ has greater cohesion than a system $\mathcal{S}_2$ of equal number of subsystems, components, and coupling, then $\mathcal{S}_1$ is more modular than $\mathcal{S}_2$ [**42**, **52**, **56**, **57**, **59**, **60**, **66**, **67**, **69**]. As seen in Fig. 7, $\mathcal{S}_1$ and $\mathcal{S}_2$ would have DSMs of the same size and the same number of interactions on the off-block diagonal. However, $\mathcal{S}_1$ would be comparatively more dense along its block diagonal.

3.2.3 *Scenario III: greater total number of modules, ceteris paribus*

If a system $\mathcal{S}_2$ has a greater number of modules than a system $\mathcal{S}_1$ of equal behaviour, then $\mathcal{S}_2$ is more modular [**52**]. While this understanding has only been explicitly stated in one measure, it has been implied many times elsewhere. Many references emphasize that each module has exactly one function [**39**, **68**, **70–75**]. If the system behaviour is held constant, this implies that the number of modules be increased until it reaches the ideal of one function per module. From the perspective of the DSM, this understanding would cause system $\mathcal{S}_2$ to have a comparatively more dense block diagonal and hence would be more cohesive. As seen in Fig. 8, $\mathcal{S}_2$ has a DSM with more well-formed modules.

3.2.4 *Scenario IV: greater distribution of subsystem size, ceteris paribus*

If a system $\mathcal{S}_2$ has a greater distribution of subsystem sizes than a system $\mathcal{S}_1$ of equal behaviour, and number of components, then $\mathcal{S}_1$ is more modular. This last comparison scenario is *asserted* without literature

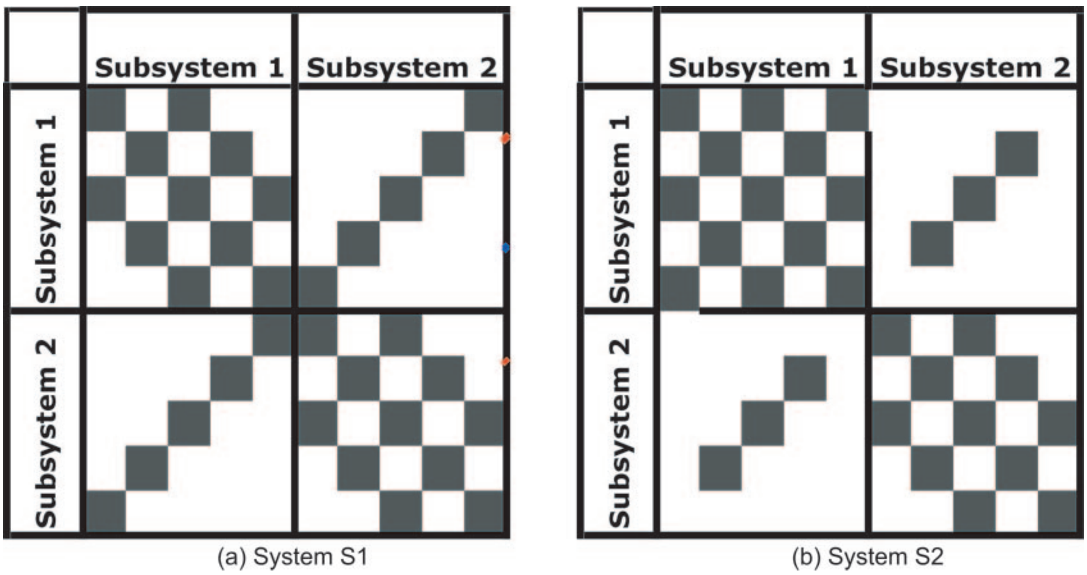


Fig. 6 Scenario I design structure matrices: greater coupling

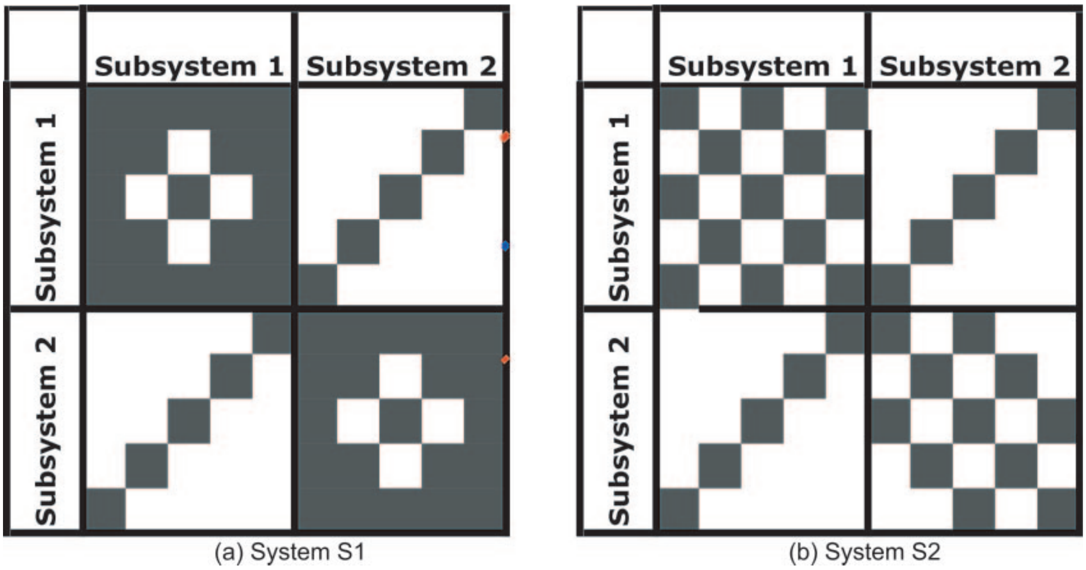


Fig. 7 Scenario II design structure matrices: greater cohesion

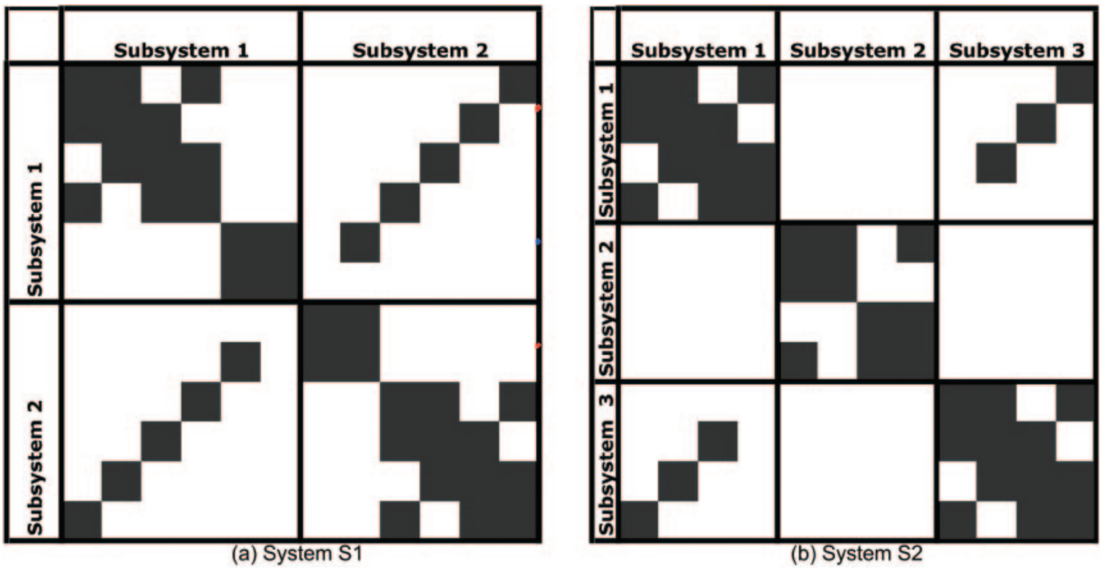


Fig. 8 Scenario III design structure matrices: greater number of modules

support. The rationale, from an abstract DSM-based point of view, is that the system with a greater distribution of subsystem sizes is going to have more densely coupled subsystems. As a result, the relative coupling is greater and the modularity should decrease accordingly. As seen in Fig. 9, $\mathcal{S}_2$ has a more dense off-block diagonal. More concretely, it is possible to imagine a PLC that is responsible for the coordination (level 3) and actuation (level 2) of a track gate. The actuation control requires a large number of sensor inputs in the vicinity of the track gate. The system would be more modular if actuation control were included as part of the track gate, so that only a small amount of information is passed between the PLC and the gate.

3.2.5 The modularity–density analogy

The past four comparison scenarios and their associated figures suggest that the literature collectively intuits modularity as a property that resembles 'planar mass density' (mass per unit area), where the 'mass–density' in the block diagonal regions of the DSM need to be maximized and the 'mass–density' in the off-block diagonal regions need to be minimized. The six previously defined variables of the DSM are given their analogues in Table 1. Stated differently, this intuition gives

$$\begin{aligned} &\mathrm{d}\Gamma/\mathrm{d}a_\mathrm{o} < 0, \qquad \mathrm{d}\Gamma/\mathrm{d}a_\mathrm{d} > 0 \\ &\mathrm{d}\Gamma/\mathrm{d}\mathcal{V}_\mathrm{o} > 0, \qquad \mathrm{d}\Gamma/\mathrm{d}\mathcal{V}_\mathrm{d} < 0 \end{aligned} \tag{7}$$

where Γ is modularity.

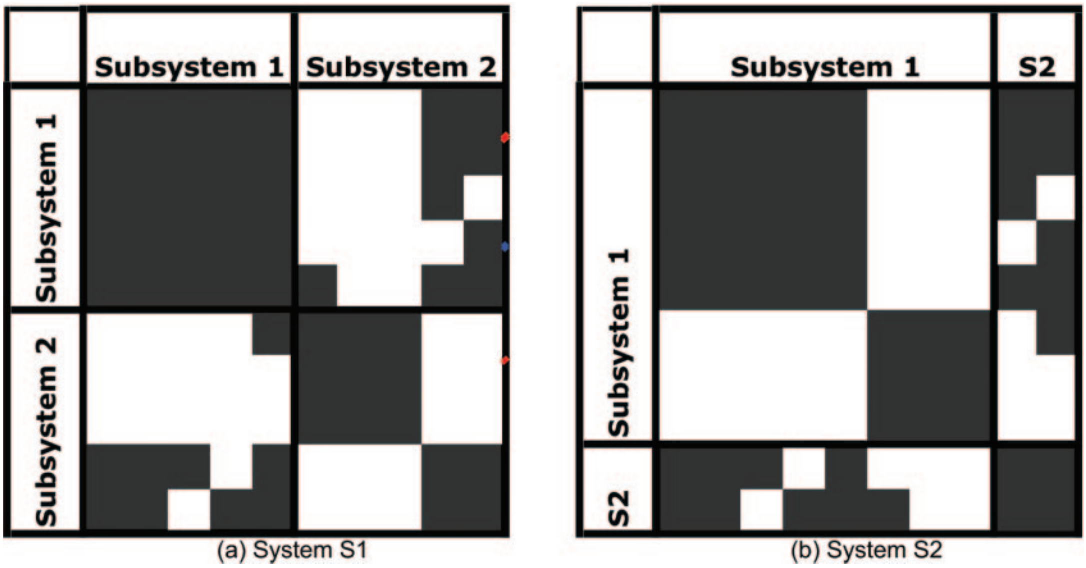


Fig. 9 Scenario IV design structure matrices: greater distribution of subsystem size

Table 1 Modularity density analogy

Modularity term	Density term	Symbol
Coupling	Off-block diagonal mass	a_o
Cohesion	Block diagonal mass	a_d
Total system interaction	Total mass	a
Total possible inter-subsystem interaction	Off-block diagonal area	$\mathcal{V}_o$
Total possible intra-subsystem interaction	Block diagonal area	$\mathcal{V}_d$
System Size	Total area	$\mathcal{V}$

3.3 Quantitative measures

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

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

where each of the variables is given in Table 2. These variables are based upon the interface matrix $I_{\varsigma_1\varsigma_2}(\imath, \jmath)$, where ς_1 and ς_2 are indices for two subsystems and $\imath$ and $\jmath$ are indices for two of their components.

This function makes a likely candidate for the measurement of modularity. It fulfils the intuition developed in the previous section and summarized in equations (7). The measure also typically gives values on the interval [0,1]. In the degenerate scenario where the off-block diagonal is denser than the block diagonal, the measure gives negative values. The measure also reaches its maximal value of unity when the off-block diagonal is empty and the block diagonal is entirely full.

Table 2 Conventional expansion of modularity variables

$a_d = \sum_{\varsigma_1}^{\sigma(S)} \sum_{\imath}^{\sigma(C_{s_{\varsigma_1}})} \sum_{\jmath}^{\sigma(C_{s_{\varsigma_1}})} \mathbf{I}_{\varsigma_1\varsigma_1}(\imath, \jmath)$	$a_o = \sum_{\varsigma_1}^{\sigma(S)} \sum_{\varsigma_2 \neq \varsigma_1}^{\sigma(S)} \sum_{\imath}^{\sigma(C_{s_{\varsigma_1}})} \sum_{\jmath}^{\sigma(C_{s_{\varsigma_2}})} \mathbf{I}_{\varsigma_1\varsigma_2}(\imath, \jmath)$
$\mathcal{V}_d = \left[\sum_{\varsigma}^{\sigma(S)} \sigma^2(C_{s_\varsigma})\right]$	$\mathcal{V}_o = \sum_{\varsigma_1}^{\sigma(S)} \sum_{\varsigma_2 \neq \varsigma_1}^{\sigma(S)} \sigma(C_{s_{\varsigma_1}})\sigma(C_{s_{\varsigma_2}})$

This function has a number of useful properties that make it suitable for modularity measurement. Firstly, it fulfils the intuition developed in the previous section and summarized in equations (7). The measure also typically gives values on the interval [0,1]. A value of unity signifies a fully uncoupled system, while in the degenerate scenario where the off-block diagonal is denser than the block diagonal, the measure gives negative values. It also introduces a level of objectivity and consistency because any DSM is characterized by six variables $(a, a_o, a_d, \mathcal{V}, \mathcal{V}_o, \mathcal{V}_d)$ with two constraints. The usage of four variables in the measure hence completely characterizes the measured system in comparison to another. Finally, it introduces the intuitively appealing units of interactions/components^2. Therefore, particularly dense regions of the DSM immediately reflect a great deal of coupling or cohesion between its associated components.

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

This picture of integration is most plausible if the system is composed of only products and resources. In such a case, the resource boundaries are equivalent to process boundaries and only a single interface exists between any two subsystems. Integration becomes a task of ensuring that the outputs of one subsystem become the inputs of another. The couplings appear as the off-block diagonal of the DSM. The presence of centralized controllers greatly complicates the reconfiguration scenario. Process and resource boundaries are no longer equivalent and instead of a single interface for a given reconfiguration, there the three shown in Fig. 5(b).

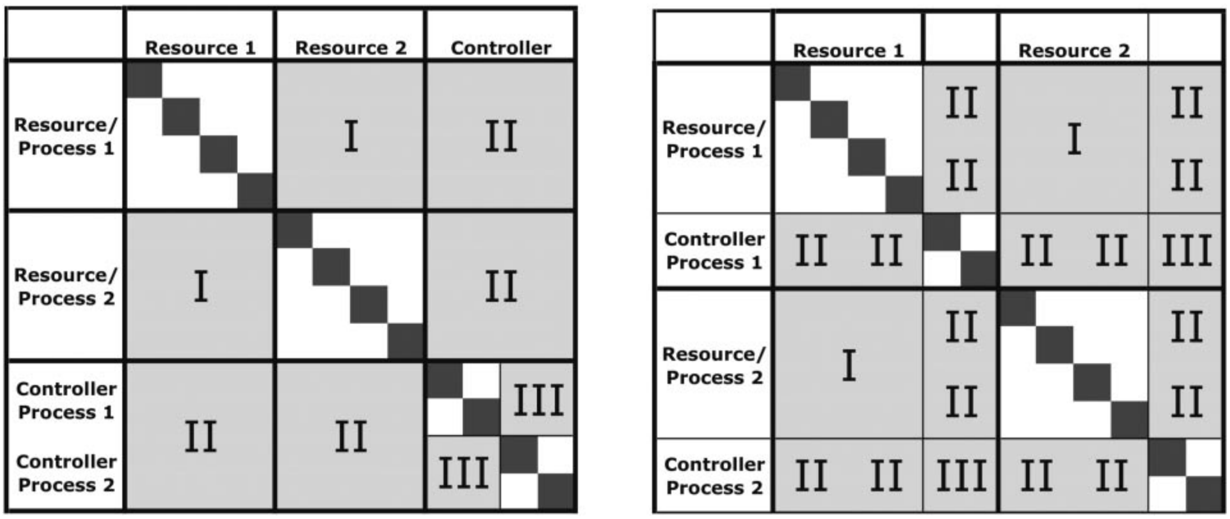
The corresponding DSM is shown on the left in Fig. 10 and each type of interface is labelled with its corresponding region in the DSM. The type I and II interfaces, as expected, appear on the off-block diagonal and therefore negatively affect the modularity measure. The type III interfaces, however,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

To overcome this problem, the concept of 'degree-of-freedom-based' [**23**] modularity is proposed as an alternative to a 'conventional' modularity. Instead of considering a module as a subsystem, a module is considered as the set of resources/components required to realize one or more complete production processes. The resulting DSM is shown on the right in Fig. 10. This concept of a module is similar to the one used in axiomatic design. Suh writes: 'A module is not a piece of hardware, although in some cases, it may coincidentally correspond to a hardware piece . . . a module is defined as the row of a matrix that yields a functional requirement when it is provided with the input of its corresponding design parameter [**74**].'

The degree of freedom-based DSM can be calculated using row and column swap operators. Specifically, the operator $\mathbf{U}_{\varsigma_1\varsigma_2}$ inserts column ς_2 immediately after column ς_1 and is explicitly defined as

$$\mathbf{U}_{\varsigma_1\varsigma_2} = [\lambda_1 \ \cdots \ \lambda_{\varsigma_1-1} \ \lambda_{\varsigma_1} \ \lambda_{\varsigma_2} \ \lambda_{\varsigma_1+} \ \cdots \ \lambda_{\varsigma_2-1} \ \cdots \ \lambda_n] \tag{9}$$

where $\varsigma_1 < \varsigma_2$, λ_i is the ith elementary column vector and $n = \sum_{\varsigma}^{\sigma(S)} \sigma(C_{s_\varsigma})$. Provided that $\varsigma_{1_i} < \varsigma_{1_{i+1}}$ and $\varsigma_{2_i} < \varsigma_{2_{i+1}}$, successive column swap operators can be



(a) Conventional DSM

(b) DOF-Based DSM

Fig. 10 Design structure matrix of two primary and one secondary resource used to move each centralized controller component to its associated degree of freedom

$$\bar{\mathbf{I}} = \left[\prod_i \mathbf{U}_{\varsigma_{1_i}\varsigma_{2_i}}\right]^{\mathrm{T}} \mathbf{I} \left[\prod_i \mathbf{U}_{\varsigma_{1_i}\varsigma_{2_i}}\right] \tag{10}$$

The degree-of-freedom (DOF)-based DSM includes type III interfaces in its off-block diagonal. However, as shown in Fig. 10, equation (9) yields type II interfaces that are now intramodular and would not count correctly as part of the existing modularity measure. To compensate for this a combination of the two matrices can ensure that all three interface types are included correctly into a modularity measure. This modularity measure uses the same functional form as in equation (8) but uses the variable expansion given in Table 3. This expansion adds the type II interfaces to the a_{o} term and subtracts them from the a_{d} using an aggregation matrix, which is defined as

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

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

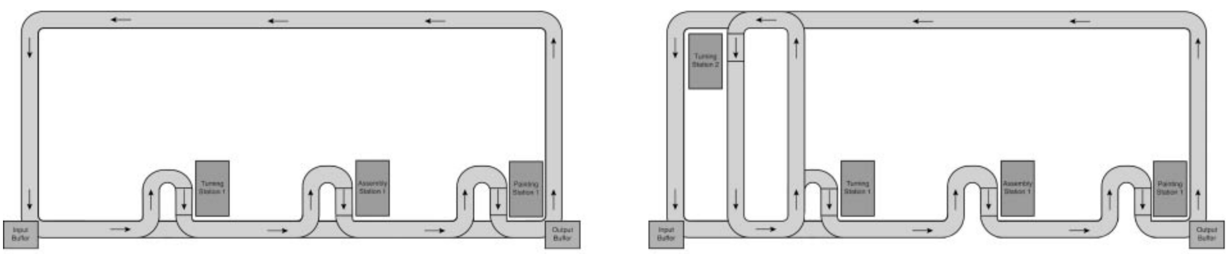
4 ILLUSTRATIVE EXAMPLE

To demonstrate the application of the manufacturing measures, the hypothetical ‘Starling’ automated manufacturing system is taken as an illustrative example. This system produces customized bird-feeders from cylindrical wooden components 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 value-adding machines had their respective execution controllers, but also used a line-wide controller to schedule the parts to each of the machines. The shuttles, however, used a distributed approach so that each had its own ‘intelligent’ software to schedule its activities. The initial configuration of the plant is shown in Fig. 11(a) while Fig. 11(b) shows it after the addition of a second turning station. The calculation of modularity is highly information intensive and much effort has to be expended initially to construct the production DSM. The component sets described in section 2.3 are used in conjunction with a production DSM method [**23**, **31**] to construct the DSM in Fig. 12(a). Finally, the conversion from a conventional DSM to a DOF-based one is completed using equation (9). These steps can be completed for each stage of the manufacturing system’s life and Fig. 12 shows the two types of DSM for stage I. At first, the appearance of the two matrices looks the same. A closer look, however, shows that the machine scheduler subsystem has been removed from the conventional DSM. The interactions associated with its columns and rows have been added to the rows and columns of the value-adding machines. Most interestingly, this transformation has caused the value-adding machines to become directly coupled where there was no coupling before.

Once the production design structure matrix has been constructed, the modularity measures may be

Table 3 Degree-of-freedom expansion of modularity variables

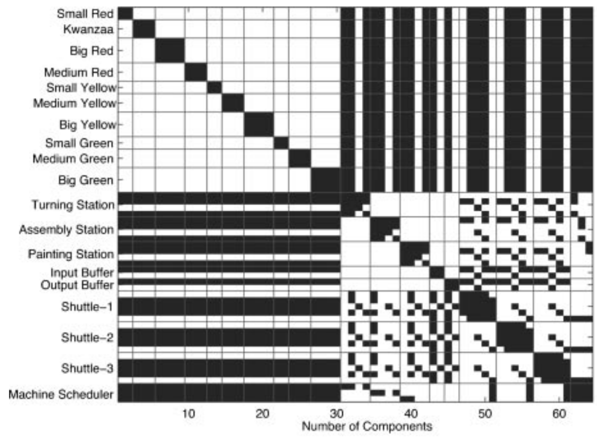
$a_{\mathrm{d}} = \sum_{\varsigma_1}^{\sigma(\bar{S})} \left[\sum_{\imath}^{\sigma(C_{s_{\varsigma_1}})} \sum_{\jmath}^{\sigma(C_{s_{\varsigma_2}})} \bar{\mathbf{I}}_{\varsigma_1\varsigma_2}(\imath,\jmath) - \sum_{\kappa}^{\sigma(Q)} \mathbf{A}(\kappa,\varsigma_1) \sum_{\imath}^{\sigma(C_{s_{\varsigma_1}})} \sum_{\jmath}^{\sigma(C_{r_\kappa})} [\mathbf{I}_{\varsigma_1 k} + \mathbf{I}_{k\varsigma_1}](\imath,\jmath) \right]$	$\mathcal{V}_{\mathrm{d}} = \sum_{\varsigma}^{\sigma(\bar{S})} \sigma^2(C_{s_\varsigma})$
$a_{\mathrm{o}} = \sum_{\varsigma_1}^{\sigma(\bar{S})} \left[\sum_{\varsigma_2 \neq \varsigma_1}^{\sigma(\bar{S})} \sum_{\imath}^{\sigma(C_{s_{\varsigma_1}})} \sum_{\jmath}^{\sigma(C_{s_{\varsigma_2}})} \bar{\mathbf{I}}_{\varsigma_1\varsigma_2}(\imath,\jmath) + \sum_{\kappa}^{\sigma(Q)} \mathbf{A}(\kappa,\varsigma_1) \sum_{\imath}^{\sigma(C_{s_{\varsigma_1}})} \sum_{\jmath}^{\sigma(C_{r_\kappa})} [\mathbf{I}_{\varsigma_1 k} + \mathbf{I}_{k\varsigma_1}](\imath,\jmath) \right]$	$\mathcal{V}_{\mathrm{o}} = \sum_{\varsigma_1}^{\sigma(\bar{S})} \sum_{\varsigma_2 \neq \varsigma_1}^{\sigma(\bar{S})} \sigma(C_{s_{\varsigma_1}}) \sigma(C_{s_{\varsigma_2}})$



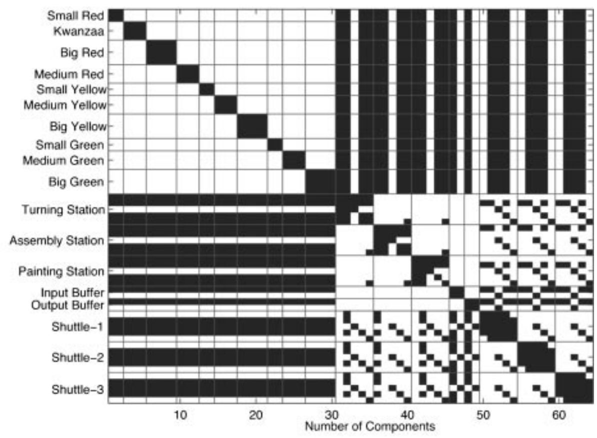
(a) Stage I

(b) Stage II

Fig. 11 Starling manufacturing system



(a) Conventional DSM



(b) DOF-Based DSM

Fig. 12 Design structure matrices of starling manufacturing system

Table 4 Modularity measures of the starling manufacturing system

	Stage I	Stage II
Modularity	0.5393	0.5319
DOF modularity	0.4449	0.4166

used to predict how easily a new resource may be introduced into the system. Table 4 shows that prior to reconfiguration the conventional measure shows a moderate level (0.5393) of modularity. However, the DOF-based value (0.4449) highlights the fact that the conventional measure may be overestimated because the type III interfaces within the machine scheduler need to be discounted from the modularity performance. In stage II, after the new resource has been added, this disparity between the two types of modularity measures grows. The conventional measure (0.5319) remains relatively constant, as it would not be expected that the introduction of an additional machine would dramatically change the average density of the block and off-block diagonals. The degree-of-freedom-based measure, however, decreases significantly (0.4166). The primary cause can be attributed to the growing role of type III interfaces that appear when more machines controlled by the machine scheduler are added. It may be expected that the two modularity values will continue to diverge as the number of centrally controlled resources grows and the associated coordination problem becomes increasingly complex. This result suggests that in order to achieve an improved modularity value a minimum of information should be passed in order to achieve the system's required coordination activities. The implications of this statement are many. First of all, it indicates that systems should coordinate their activities with a minimum of information. Secondly, this statement gives initial quantitative support to many distributed manufacturing system design approaches that specifically try to minimize the number of messages passed between physical agents. The effects of such measures would be to reduce the density of the off-block diagonal and ensure that it stays relatively constant as the size of the systems grows with each reconfiguration.

5 CONCLUSIONS AND FUTURE WORK

In the last three sections, two variants of manufacturing modularity were developed as measures of reconfiguration ease. Firstly, interface complexity was argued to have a strong effect on modularity. Next, the literature was analysed to develop a qualitative understanding of modularity. Finally, the manufacturing modularity measures were synthesized from this understanding of modularity and manufacturing interfaces.

Both modularity measures provide a quantitative description of *how many* interface parameters there are between production subsystems. Meanwhile, any of the desired set of reconfigurations would necessarily have to pull apart and put back together these interfaces. The ease of this process would depend on how few interface parameters needed to be changed. Mathematically, the number of interface parameters changed is given by

$$\sum_{\varsigma_1}^{\sigma(\bar{S})} \sum_{\varsigma_2}^{\sigma(\bar{S})} \sum_{\imath}^{\sigma(C_{s_{\varsigma_1}})} \sum_{\jmath}^{\sigma(C_{s_{\varsigma_2}})} \Delta\mathbf{I}_{\varsigma_1\varsigma_2}(\imath, \jmath) \tag{12}$$

where $\Delta\mathbf{I}_{\varsigma_1\varsigma_2}(\imath,\jmath)$ is the bitwise comparison of the initial and final design structure matrices $\mathbf{I}$ and $\bar{\mathbf{I}}$ respectively

$$\Delta\mathbf{I}_{\varsigma_1\varsigma_2}(\imath,\jmath) = \begin{cases} 0 & \text{if } \varsigma_1 = \varsigma_2 \\ \mathbf{I}_{\varsigma_1\varsigma_2}(\imath,\jmath) & \text{if } \varsigma_1 \neq \varsigma_2 \text{ and } \bar{\mathbf{I}}_{\varsigma_1\varsigma_2}(\imath,\jmath) \text{ does not exist} \\ \bar{\mathbf{I}}_{\varsigma_1\varsigma_2}(\imath,\jmath) & \text{if } \varsigma_1 \neq \varsigma_2 \text{ and } \mathbf{I}_{\varsigma_1\varsigma_2}(\imath,\jmath) \text{ does not exist} \\ |\mathbf{I}_{\varsigma_1\varsigma_2}(\imath,\jmath) - \bar{\mathbf{I}}_{\varsigma_1\varsigma_2}(\imath,\jmath)| & \text{otherwise} \end{cases} \quad (13)$$

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

Finally, this development of manufacturing modularity is the second of two papers in this issue that propose elements of an integrated reconfigurability measurement process based upon the principles of reconfiguration potential [**23**, **25–27**] and reconfiguration ease [**26**, **32**, **30**, **33**, **27**]. Future work seeks to unite these complementary principles in the context of case studies at the conceptual, laboratory, and industrial scales [**23**]. More formalized research to develop methodologies for realizing the measurement process are ongoing [**31**, **76**, **77**].

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APPENDIX

Notation

a	total behaviour
a_d	total cohesion
a_o	total coupling
C_b	independent buffer components
C_h	material handling components
C_l	product components
C_m	transforming machine components
C_q	centralized controller components
C_{s_ς}	set of subsystem components for subsystem s_ς
I	design structure matrix
S	set of subsystems
U	unitary operator
V	total possible interaction
V_d	total possible intrasubsystem interaction
V_o	total possible intersubsystem interaction
Γ	Modularity
ι, j	indices for subsystem components
$\sigma(\ )$	size of set operator
ζ_1, ζ_2	indices for components