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Assessing the structural complexity of manufacturing systems configurations

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Abstract Modern manufacturing systems are increasingly required to be flexible and adaptable to changing market demands, which adds to their structural and operational complexity. One of the major challenges at the early design stages is to select a manufacturing system configuration that both satisfies the production functional requirements and is easy to operate and manage. A new metric for assessing the structural complexity of manufacturing system configurations is presented in this paper. The proposed complexity metric incorporates the quantity of information using an entropy approach. It accounts for the complexity inherent in the various modules in the manufacturing system through the use of an index derived from a newly developed manufacturing systems classification code. The code captures the effect of various component types and technologies used in a manufacturing system on the system's structural complexity. The presented metric would be helpful in selecting the least complex manufacturing system configuration that meets the requirements. An engine cylinder head production system is used to illustrate the application of the proposed methodology in comparing feasible but different manufacturing system configurations capable of producing the cylinder head based on their structurally inherent complexity.

Keywords Complexity · Manufacturing system · Reconfiguration

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1 Introduction

Today's competitive manufacturing environment forces companies to be responsive to changes in the market and satisfy the need for mass customization through flexibility and adaptability in order to survive and be globally successful. Companies strive to increase their range of products and implement a production system that can be re-configured for the unexpected market changes in order to achieve the desired agility. This trend is one of the reasons why manufacturing systems have become more complex and difficult to manage. Wiendahl and Scholtissek (1994) have reviewed the sources of complexity in production systems and pointed out the various approaches adopted by industry as well as those developed by the research community to cope with complexity in manufacturing systems.

This paper will present a metric for assessing the complexity of manufacturing system configurations in order to help the decision makers compare the various alternatives. An introduction to reconfigurable manufacturing systems and literature review of relevant research in manufacturing systems complexity are provided. The advantages and the disadvantages of various complexity measures are discussed. A system complexity metric that accounts for both the quantity of information as well as variety of modules and technologies within a manufacturing system is proposed. A newly developed manufacturing systems code used to formulate the modules type complexity index is briefly described. A case study is used to illustrate the application of the proposed complexity metric in order to compare manufacturing systems configurations.

2 Reconfigurable manufacturing systems and complexity

The changing manufacturing environment requires creating production systems that are themselves easily up-gradable to incorporate new technologies and new functions. Reconfigurable Manufacturing Systems (RMS) represent a visionary challenge for manufacturing enterprises and are viewed as an adaptation mechanism to cope with the changing production environment (Koren et al. 1999). USA's National Research Council has identified reconfigurable manufacturing as first priority among six grand challenges for the future of manufacturing (1998).

Unlike traditional manufacturing systems, RMS can be achieved by using reconfigurable hardware and software, such that its capacity and/or functionality can be changed over time. The reconfigurable components include machines and material handling systems, mechanisms and modules for individual machines, as well as sensors, process plans, production plans, and system control algorithms for entire production systems.

The reconfiguration of a manufacturing system is considered whenever there is a new circumstance that warrants such a change. These circumstances may be changing product demand, the introduction of new products, or the integration of new process technology into existing manufacturing systems. There might be several configuration alternatives to consider before selecting a new configuration. The objective is to adapt to the new conditions without unduly increasing the system cost or complexity, or degrading the resulting product quality.

2.1 Manufacturing systems complexity

Manufacturing systems are often described as being complex. The dynamic nature of the manufacturing environment greatly increases the number of decisions that need to be made and the integration of many software and hardware functions makes it difficult to predict the effect of a decision on the system performance.

A complex system is one whose static structure or dynamic behavior is counterintuitive or unpredictable (Deshmukh et al. 1998). Complex systems share certain features such as comprising a large number of elements, having high dimensionality, and representing an extended space of possibilities. The causes of complexity should be analyzed in order to be able to cope with decision-making difficulties in integrated manufacturing systems. The increase in complexity due to the introduction of new technologies and the integration of different components of manufacturing systems is only justifiable by improved system performance but should otherwise be minimized.

2.1.1 Entropy/information content approach

There are two main approaches in published literature to quantify systems complexity. The first uses Shannon's (1949) information theory/entropy approach. Researchers such as Deshmukh et al. (1998), Frizelle and Woodcock (1995), and Sivadasan et al. (2006) define the notion of static complexity and dynamic complexity based on the entropy formula. Static complexity accounts for the structure of the components of a system and the relationships among them whereas dynamic complexity deals with the operational behavior and schedule changes of the system. The static complexity of a system S can be measured by the amount of information needed to describe the system and its components:

$$H(S) = -\sum_{i=1}^{M}\sum_{j=1}^{N} p_{ij}\log_2(p_{ij}) \tag{1}$$

S = System S
M = number of resources
N = number of possible states for the ith resource
p_{ij} = probability of resource i being in state j

Zhang and Efstathiou (2004) assess the complexity of mass customization systems consisting of a push line and a pull line where an inventory area is used as a decoupling point between the two. In their multi-product supply chain model, the probability of each resource state is defined by the probability of producing a product at a specific time. The authors assumed, due to the lack of data, the worst-case scenario where all events have the same probability of occurrence, which leads to maximum complexity.

Another entropy approach to measure complexity is the information content concept in Axiomatic Design (Suh 1999). Suh's complexity metric is defined as a measure of uncertainty in achieving the functional requirements of a design task. Based on this definition, the variable p in Eq. (1) is defined as the probability of success of the design parameters in meeting the functional requirements. Suh (2005) classifies complexity into two categories: time-independent complexity and time-dependent complexity. This is similar to Frizelle's (1995) classification of static and dynamic complexity. In addition, time-independent complexity is further decomposed to add the complexity arising from the designer's perception. The time-dependent complexity is either combinatorial or periodic. It has been proposed that converting combinatorial complexity to a periodic one re-sets and reduces the time dependent complexity. This approach to modeling dynamic complexity provides insight and guidelines to reduce complexity rather than assessing it with a metric. The metrics provided by using Axiomatic Design are for both time-independent real and imaginary complexities.

Information theory based measures of system complexity provide objective data. However, two important issues should be considered when applying the entropy approach. The first is related to determining which event to use in order to describe the state of a system component. The second is the deficiency arising from the assumptions of independence between system components made in the entropy approach to simplify the formulation. In reality, system components usually have some interdependencies; hence, conditional probabilities should be used. The resulting equation to measure the information content would be very complex for a system with many components. In Suh's (1999) approach, similar issues arise for decoupled designs where it may be difficult to define the design requirements' range.

2.1.2 Heuristic approaches/indexes

The second approach to quantify systems complexity is to use heuristics and develop indices. Kim (1999) addresses the issue of manufacturing systems complexity considering the increase in product variety and the need to reduce the system complexity arising from it. The author claims that in lean manufacturing, system complexity as affected by increased product variety is much less than in an equivalent mass production system. In order to prove this thesis, a series of system complexity measures were proposed based on a complexity model developed from a systems theory perspective including:

- *Relationships between system components*
  - Number of flow paths
  - Number of crossings in the flow paths
  - Total travel distance of a part
  - Number of combinations of products and matching machines
- *Elementary system components*
  - Number of elementary system components
  - Inventory level

Each one of the above variables provides some insight into the effect of various components of a manufacturing system structure. The fact that these elements are not combined into a single system complexity metric makes it difficult to compare system configuration alternatives. In addition, a classification or relative importance of these factors was not developed, hence it is difficult to compare.

Urbanic and ElMaraghy (2004) provide a heuristic model where a process complexity metric is proposed and used to compare different manufacturing methods for a single product. This model differs from the previous studies by combining the absolute quantity of information, the diversity of information and information content, i.e., the "relative" measure of effort, and the human operator perception of an operation complexity to achieve the required result. The three elements of manufacturing complexity are decoupled and re-linked using a systematic, simple, and concise methodology. From this point of view, the metric provides a hybrid approach that combines indices and entropy to measure the complexity for manufacturing operations and processes and takes into consideration the human perception. The proposed process complexity does not take into account some system level components such as transporters and buffers, and the complexity arising from their operation and management.

Previous studies on assessing the complexity of manufacturing systems have focused on: (a) the entropy based generalized objective metrics, and (b) case dependent subjective indices. The entropic measures provide objective means of comparing systems, whereas the heuristic indices provide a better insight into the effects of system elements. There seems to be a lack of a comprehensive metric that combines both the amount of information and the type of information needed to describe a system complexity.

3 Measuring the manufacturing systems complexity

The reported research addresses the time-independent structural complexity of the building blocks of a manufacturing system including machines, transporters, and buffers. It captures the complexity arising due to their structural characteristics, used technologies and degree of operational difficulty. These inherent complexities are particularly important at the initial system design stages where alternative equipment and technologies may be considered with potentially major different cost implications. There are two phases in designing a manufacturing system. The first is the selection of the type, features and number of pieces of equipment that all have varying degrees of complexity based on the amount of information required to operate, program and use them. This is the static structural design phase, where the proposed complexity metric would be used to help select equipment keeping their inherent complexity in mind. The second phase further details the system design, equipment placement, the flow pattern and fine tune the number of pieces of equipment based on the operation characteristic of the system as a whole and its dynamic behavior and interaction between its modules. This is where discrete events and other simulations and several tools such as balancing techniques would be used. The proposed manufacturing system configuration complexity metric does not assess complexities arising from the system dynamic behavior during operation including scheduling, bottleneck, throughput, production capacity and the like.

The manufacturing system complexity is defined by the uncertainty level of its system state. Internal and external disturbances are a source of complexity in a manufacturing system. Disturbances such as equipment failure or shortage of WIP increase the operational difficulty. Hence, a system structure that is more likely to generate such disturbances, due to its technology or structural design, is considered more complex. The results of this work will help designers/researchers in their effort to quantify the effect of this complexity on the system performance.

The following section defines the manufacturing system representation for evaluating the complexity, and it will be followed by an explanation of how the various components and technologies contribute to the overall complexity of manufacturing systems.

3.1 Manufacturing system representation

A mathematical model to represent a reconfigurable manufacturing system is presented and its use is illustrated with a case study. A reconfigurable manufacturing system that consists of modular multi-spindle machine tools is considered. Each machine consists of a base structure to which several modules can be added or removed as capacity requirements change (Spicer 2002). An addition or removal of a module does not change the process capability of a machine but changes its capacity. An example of this is the addition of a spindle or machine head. It is assumed that the machine modules are functionally parallel; i.e., a machine can continue to operate even if one module fails. However, modules are functionally serial with the machine base. Therefore, if “the base” of the machine, which supports, integrates, and controls all modules, fails, the whole machine and its modules fail. This RMS model includes a series of machines where each stage is represented by a unidirectional piece flow. Each stage consists of a set of

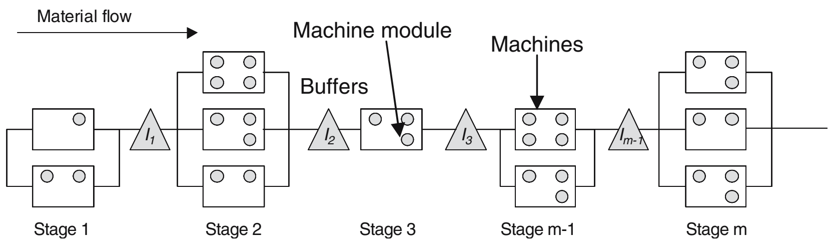


Fig. 1 Manufacturing System Representation (Spicer 2002)

machines assigned to accomplish a set of tasks defined according to a process plan (Fig. 1).

3.2 Proposed system complexity metric

Since the selection of a manufacturing system configuration is made in the early design stages, a structural complexity index provides a good description of the inherent complexity of its components, the relationship among them, and their influence. Dynamic complexity is more applicable to the system time-dependent behavior and requires data normally obtained during actual operations or simulation of the shop floor. The proposed complexity measure is an entropy-based index that uses the reliability of each machine to describe its state in the manufacturing system, combined with an equipment type code index coefficient to incorporate the effect of the various hardware and technologies used. In addition to the state of each machine in the system, transporters and buffers also introduce complexity since their utilization needs to be managed in order to run the production without disruption. Since each resource in a manufacturing system is a potential source of uncertainty (i.e., complexity), the buffers should be considered as well as the material handling systems and their type. Based on these considerations, the total complexity of an RMS is a function of:

- Number, type, and state of machines
- Number, type, and the state of buffers
- Number, type, and state of the material handling system and its components

$$H_{\mathrm{RMS}} = w_1 H_{\mathrm{M}} + w_2 H_{\mathrm{Buffer}} + w_3 H_{\mathrm{MHS}} \tag{2}$$

where H_{M} represents the complexity arising from the machines, H_{Buffer} is the complexity of buffers, and H_{MHS} represents the material handling system complexity. The relative weights of the elements that contribute to the overall complexity are represented by w_1,w_2, and w_3 respectively. It is believed that all three contributors to the structural complexity are equally important. However, these weights can be used should a reason exist to differentiate between various elements by varying the components' relative degree of importance (Fujimoto et al. 2003). The value of these weights may reflect the system designer's subjective preferences based on experience or can be estimated using tools such as the Analytic Hierarchy Process (AHP).

3.2.1 Machine complexity metric

The following equation expresses the complexity due to the machines:

$$H_{\mathrm{M}} = \sum_{i=1}^{M} \sum_{j=1}^{N} X_{ij} a_{ij} \sum_{k=1}^{2} p_{ijk} \log_2 \left(\frac{1}{p_{ijk}} \right) \tag{3}$$

where

p_{ijk} = Probability of a machine's state at stage i of machine configuration j
a_{ij} = Type index of machine X_{ij}
X_{ij} = number of machines in stage i at machine configuration j
N = maximum number of modules installed in a machine
M = number of stages in a system configuration

The probability of a machine that operates at full capacity p_{ijk} is calculated based on the machine configuration assumptions explained in 3.1. It is assumed that any component of a machine can have two states: operation or failure. The following probabilities can be calculated for each machine configuration:

$$\begin{cases} p_{ij1} = R_{\mathrm{B}} \left(1 - \prod_{i=1}^{n} U_i \right), & \text{Reliability of a machine with configuration } j \\ p_{ij2} = 1 - p_{ij1}, & \text{failure probability of a machine with configuration } j \end{cases} \tag{4}$$

where

R_{B} = the reliability of the base
U_i = failure probability of a module i
n = the number of modules installed in the machine

Based on Eq. (3), the machine complexity metric has been defined by the entropy of a two-event system, the states of which have been defined by Eq. (4). Since the entropy of any two events state system is symmetric about 1/2, two identical machines with reliability values of 0.7 and 0.3 represent the same uncertainty level. If the dynamic system behavior is considered, then the machine that has higher reliability should be selected based on its throughput performance. However, for the static complexity notion of a manufacturing system, which is defined by the uncertainty level with respect to defining its state, the two machines are equally complex.

As stated previously, the type of each machine and its features affect the complexity of a manufacturing system. A multi-purpose machine has many features and each feature can offer different options. The increase in different setting possibilities will also increase the complexity of operating and programming a machine; therefore, the more flexible the machine, the more complex it is. The index a_{ij} used in Eq. (3) reflects the differentiation between various equipment types and their technologies, and its computation is presented in Section 3.3.

3.2.2 Buffer type complexity

The second component of a manufacturing system complexity is related to the buffers. In a manufacturing system consisting of M stages there could be a maximum of (M–1) locations for the buffers. It is assumed that the number of product variants that can exist in the system is k, and that the variants are being produced in batches. In order to describe the state of the buffers, two aspects are analyzed (Zhang and Efstathiou 2004):

$$H_{\text{Buffer}} = H_{\text{B1}} + H_{\text{B2}} \tag{5}$$

- H_{B1}, The state of the buffer i.e. whether it is empty or not.
- H_{B2}, The product variant in the system.

The complexity caused by the empty/non-empty state in each location, H_{B1} is calculated as follows:

$$H_{\text{B1}} = \sum_{i=1}^{M-1} b_i \left(p_{i\text{ne}} \log_2\left(\frac{1}{p_{i\text{ne}}}\right) + p_{i\text{e}} \log_2\left(\frac{1}{p_{i\text{ie}}}\right)\right) \tag{6}$$

where

$p_{i\text{e}}$ = Probability of ith buffer being empty
$p_{i\text{ne}}$ = Probability of ith buffer being non-empty
b_i = Buffer type index
M–1 = number of buffers = number of stages–1

The role of buffers in a manufacturing system is to provide storage for WIP and also to ensure that the downstream operations are not starved and the production is not disrupted. The key concern is to have sufficient quantity of WIP in order to run the production. In a push type manufacturing system, an empty state of a buffer means the accumulation of WIP in the upstream processes, starvation of downstream processes, and as a result, the disruption of the production. This state of a system would lead to complexity related to managing its use, programming and operation to ensure sufficient supply of parts. Therefore, the ‘‘empty’’ and ‘‘non-empty’’ buffers states represent two critical states, which affect the complexity of using and operating these modules of a production system.

The probability of a buffer being empty or non-empty may not be available at the early design stages of a manufacturing system. These probabilities can be estimated by using simulation approaches or can be set to a pre-determined value. Other studies related with finding the steady state probabilities for buffer states used simulation, markov chain and markov process formulations, which are beyond the scope of this paper (Kouikoglou 2002; Baral 1993). This shows that such quantities can be estimated for various types of manufacturing scenarios including push and pull operation strategies.

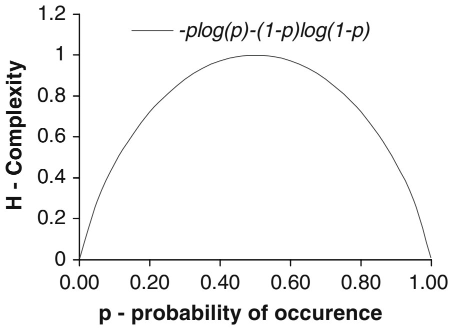
The metric proposed in this paper deals with push type and batch style manufacturing where it can be assumed that the production stops when WIP level at any location is zero. Moreover if we look at the economic order quantity (EOQ) model where a deterministic constant demand scenario is considered, the average level of inventory is 1/2 of the inventory capacity. This means that the frequency of having an empty and full buffer is equally probable. Zhang and Efstathiou (2006) analyze the complexity of different types of inventory strategies with EOQ model. Another way of defining these probabilities is to consider the worst-case scenario for the buffers where, in the limit, it reaches the maximum level of complexity.

In a system where two events exist to describe the state of buffers, the maximum complexity arises when their probabilities of occurrence are equal. Figure 2 shows that the maximum complexity is equal to 1 for each buffer location. As a result, H_{B1} would be equal to the number of buffers in that system.

In order to calculate H_{B2}, the complexity caused by the assignment of the product variant in the system can be expressed as:

$$H_{\mathrm{B2}} = \sum_{i=1}^{M-1} \sum_{j=1}^{k} p_{ij} \log_2 \left(\frac{1}{p_{ij}} \right) \tag{7}$$

Fig. 2 Entropy reaches maximum when both events have equal probability of occurrence



where

p_{ij} = Probability of the ith buffer containing product variant j
k = Number of product variants
M–1 = number of buffers

In batch production, the buffers can contain any product variant at a point of time where a decision needs to be made regarding the schedule and the sequencing of the production. Hence, it is necessary to know which variant exists in a buffer. The uncertainty here is represented by the quantity of information that is required to determine the amounts of WIP in various buffers of a system for a specific product variant.

In a dedicated storage buffer system, each item is stored in specific locations in the factory, which, from a configuration design perspective, means that the capacity at each location must be sufficient to accommodate its highest expected inventory level. However, automated storage and retrieval systems (AS/RS) provide a centralized random access strategy where the items are stored in any available location (Fig. 3). The flexibility of AS/RS's reduces the floor space used for storage. In addition, automated systems improve the control and management of inventory levels, thanks to their computerized control system.

The index b_i used in Eq. (6) differentiates between various storage technologies and strategies used in manufacturing systems based on their type complexity. A higher digit value for buffer Type Code represents increased options for managing buffers, and hence, increases their complexity. The introduction of this new type index captures the complexities inherent in different buffer strategies, technologies, and management, in addition to the state of buffers that was accounted for earlier.

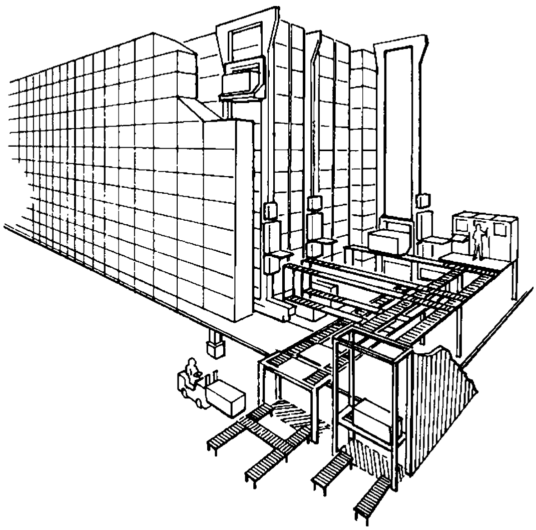


Fig. 3 AS/RS system (http://www.ie.ncsu.edu/kay/mhetax/StorEq/)

3.2.3 Material handling systems complexity

Material handling systems (MHS) provide flexibility depending on their features. A uni-directional conveyor would only provide one fixed route whereas a self-guided AGV can provide several options for alternate process plans as well as alternative routing to cope with machine failures. In order to capture these differences, the complexity of various MHS technologies and types is represented similarly to the machine types.

The complexity of material handling systems is calculated as follows:

$$H_{\mathrm{MHS}} = \sum_{t=1}^{T} m_{\mathrm{t}} \sum_{k=1}^{2} p_{\mathrm{tk\ MHS}} \log_2\left(\frac{1}{p_{\mathrm{tk\ MHS}}}\right) \tag{8}$$

where

$p_{\mathrm{tk\ \ MHS}}$ = Reliability of MHS
m_{t} = MHS type index
T = number of transporters used in MHS
k = state of transporter t

The T in Eq. (8) represents the number of transporters used in the system. In the case of conveyors, it is the sum of the number of conveyor segments used. For example, three conveyors are required in a system that includes three parallel machines. For a uni-directional flow line where the stations are placed along the conveyor, it is considered as one transporter only. In a manufacturing system where AGVs are used, T is the total number of AGVs.

3.3 Type complexity of machines, buffers, and MHS

A new manufacturing system Group Technology like code developed by ElMaraghy (2004) represents the information required to describe the various types of equipment. Digits within each field are used to represent: (1) Type and general structure, (2) Controls, (3) Programming, and (4) Operation of a system component or module. The number of such resources and variety within a class all add to the overall required quantity of information to use and control them.

The classification part of the developed type code is only summarized here as it is used to formulate the modules type complexity index. The code uses a string representation to capture the main sources of inherent structural machine complexity. The first field describes the component type or structure. The control, programmability and operation features are captured in the second, third and fourth fields respectively. The developed code accounts for the main modules in manufacturing systems: machines of various types, transporters and buffers. Any other components that cannot be considered under these categories are not included at present. The type fields for machines, buffers, and material handling systems are shown below. V represents the total number of the sub-components represented by each digit.

3.3.1 Machine type code

Machine Type Code – Field 1									
Structure	Axes	Heads	Spindles	Tooling		Tool Magazine	Fixtures		Buffers
				Fixed	Adjust.		Fixed Pin	Special	
V_{d1}	V_{d2}	V_{d3}	V_{d4}	V_{d5}	V_{d6}	V_{d7}	V_{d8}	V_{d9}	V_{d10}

The Machines Complexity Type Code (ElMaraghy 2004; ElMaraghy et al. 2005) is as follows:

Digit no.	Value	Description
1		*Structure*
	1	fixed/dedicated
	2	fixed/modular
	3	expandable/dedicated
	4	expandable/modular
2	1	axes of motion
3	2	heads installed
4	2	spindles
5	0	fixed tools
6	60	adjustable tool
7		*Tool Magazine*
	0	none
	1	fixed
	2	replaceable
8	4	fixed pin fixtures
9	0	moving pin/supports fixtures
10		*Integrated Buffers*
	0	none
	1	FIFO
	2	indexing table

In order to compute the coefficient a_{ij} in Eq. (3), the type and general structure field is converted/aggregated into a single number using the following formulation, which normalizes the value of each digit and each field:

$$a_{ij} = \frac{\sum_{d=1}^{ND} \frac{V_d}{MV_d}}{ND} \tag{9}$$

where

V_d = Value of digit d

MV_d = Maximum value of digit d
a_{ij} = Type index of machine X_{ij}
ND = Total Number of Digits for the field

The converted type index coefficient a_{ij} represents the relative complexity of a machine compared to the most complex machine type defined by the proposed code representation. The following values are considered reasonable maximum values for the features represented in the code. The numbers used in the coding system are based on best available data and experience. As more research and data become available, these numbers can be refined. But since the same numbers are used for all systems being considered, they are good enough for the purpose of comparing systems, much like the constants used in applying the DFA analysis method. These upper limits may change as machine technology evolves. In the type complexity code, the degree of complexity of various pieces of equipment in each range has been defined and ranked to capture the increasing number of choices and decisions to be made for that characteristic of a machine, buffer, or MHS.

Maximum Machine Type Code

Structure	Axes	Heads	Spindles	Tooling		Tool Magazine	Fixtures		Buffers
				Fixed	Adjustable		Fixed Pin	Special	
4	*5*	*4*	*4*	*100*	*160*	*2*	*20*	*10*	*2*

As an example, consider the multiple-spindle horizontal machining centre shown in Fig. 4 (http://www.sw-machines.com/en/indexe.html). The corresponding machine type code would be:

1. A machine with fixed structure
2. 4 axes of motion
3. 2 heads installed
4. 2 spindles
5. 0 fixed tools
6. 60 adjustable tool

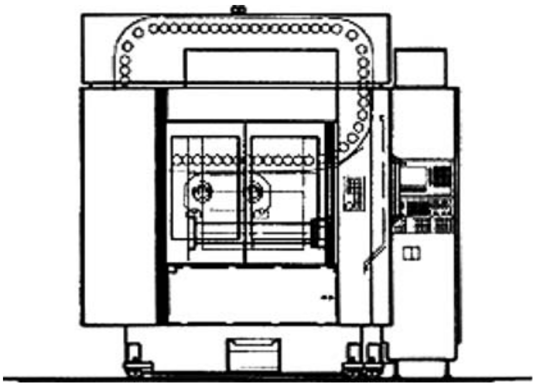


Fig. 4 Horizontal Machining Centre

7. 1 – Fixed tool magazine
8. 4 fixed pin fixtures
9. 0 moving pin/supports fixtures
10. 0 – no integrated buffers

The type code string for this machine is:

1	4	2	2	0	60	1	4	0	0

Using the formula in Eq. (9), the machine type complexity index is evaluated as follows:

$$a_{ij} = \frac{\left(\frac{1}{4} + \frac{4}{5} + \frac{2}{4} + \frac{2}{4} + \frac{0}{100} + \frac{60}{160} + \frac{1}{2} + \frac{4}{20} + \frac{0}{10} + \frac{0}{2}\right)}{10} = 0.31$$

Another machine configuration, shown in Fig. 5, has been described using the type code index (http://www.komaprecision.com/tsudakoma/ Tsudakoma%20 Main.htm):

1. 4 A machine with modular expandable components
2. 3 axes of motion on the spindle column
3. 1 head installed
4. 4 Horizontally mounted modular spindles with automatic tool changers with the capability to have 1 to 4 spindles
5. 4 fixed tools
6. 160 adjustable tools
7. 1 Capability to machine one face of a cylinder head at one angle of orientation per fixture set-up. Fixed tool magazine
8. 4 fixed pin fixtures
9. 6 moving pin/supports fixtures
10. 0 no integrated buffers

The type code string for this machine is:

4	*3*	*1*	*4*	*20*	*160*	*1*	*4*	*6*	0

Fig. 5 Multi spindle rotary table machining centre

Using the formula in Eq. (9), the machine type complexity index is:

$$a_{ij} = \frac{\left(\frac{4}{4}+\frac{3}{5}+\frac{1}{4}+\frac{4}{4}+\frac{20}{100}+\frac{160}{160}+\frac{1}{2}+\frac{4}{20}+\frac{6}{10}+\frac{0}{2}\right)}{10} = 0.54$$

The comparison of these two machines shows that as the capability of a machine increases, the value of the machine type index also increases. The first machine has a fixed structure, fewer numbers of spindles, and a reduced tool holding capacity. The second machine is able to handle more tasks than

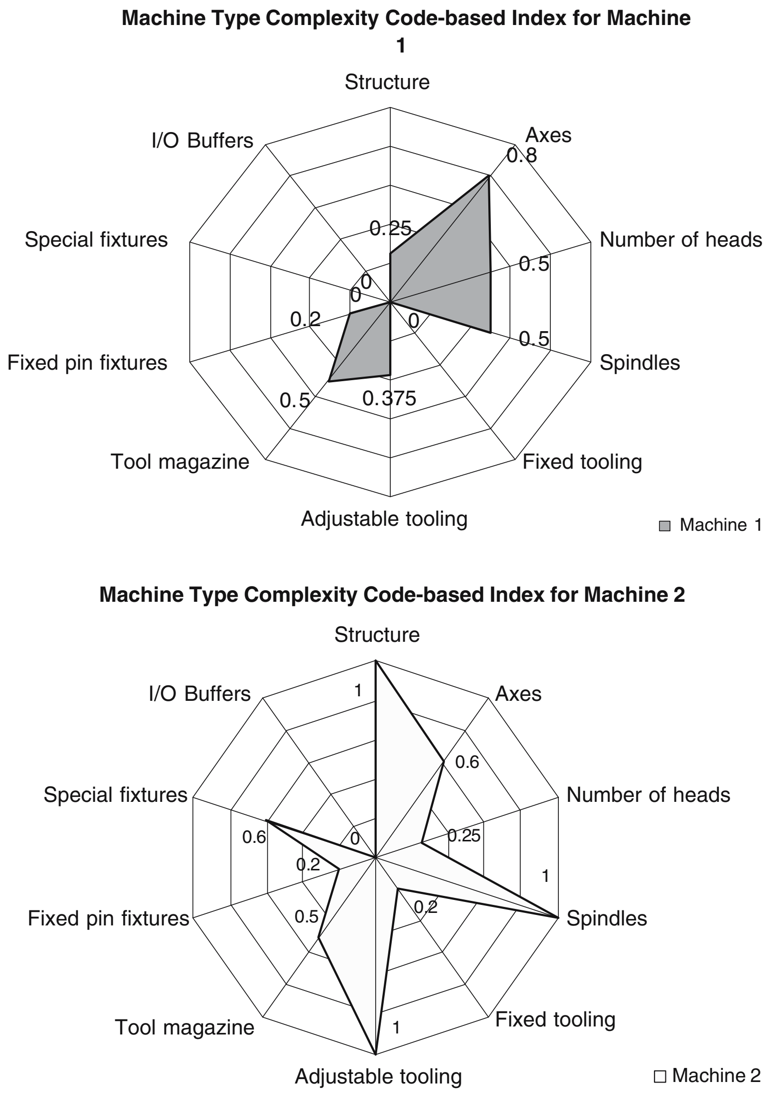


Fig. 6 Relative Complexity presentation of different machine types

machine 1 based on increased number of heads, installed spindles, and fixture features; hence, the value of the type code is higher as illustrated in Fig. 6.

The type complexity index of machine 2 is equivalent to 0.54 on a 0 to 1 scale. The higher the value of each digit the more complex the machine, and this index means that the type complexity of the considered machine is 54% compared with the most complex machine that can be represented by this code format, which is a function of the maximum value of each code digit.

3.3.2 Buffer type code

The type index b_i, in Eq. (6), is used in order to differentiate between the various types and technologies of buffer used in a system. It is calculated in a manner similarly to the machine type index using the following buffer type code representation (ElMaraghy 2004) and Eq. (9):

Buffers Type Code – Field 1		
Buffer structure	Equipment technology	Capacity
V_{d1}	V_{d2}	V_{d3}

Buffer Type Code (ElMaraghy 2004)

Digit no., value and description

1. Buffer Structure
    1. manual
    2. FIFO
    3. LIFO
    4. indexing

2. Equipment Technology
    1. magazine (dedicated)
    2. carousel (dedicated)
    3. random access system

3. Capacity
    1. Storage capacity

3.3.3 MHS type code

The type index for MHS, m_t, is calculated using the following code representation and Eq. (9).

Material Handling Systems Type Code – Field 1		
Structure	MHS equipment used between stages	MHS equipment used within process/cell
V_{d1}	V_{d2}	V_{d3}

MHS Type Code (ElMaraghy 2004)

Digit no., value and description

1. Conveyor Structure
   1. un-powered (gravity)
   2. powered, unidirectional, synchronous
   3. powered, unidirectional, asynchronous
   4. powered, bi-directional, synchronous
   5. powered, bi-directional, asynchronous

2. Equipment Technology among processes
   1. Manual
   2. Conveyor
   3. Gantry robots
   4. Guided rail vehicles
   5. Automated guided vehicles

3. Equipment Technology within processes/cell
   1. Manual
   2. Conveyor
   3. Gantry robots
   4. Guided rail vehicles
   5. Automated guided vehicles

The type code captures various MHS technologies used in a manufacturing environment. A belt conveyor can transport work-in-process inventory between the stages; however, its failure would result in a serious disruption of the material flow. The use of AGVs provides several benefits such being part of a centralized storage retrieval system, more flexible routing of products, and ability to continue production despite of failure of single AGV (Fig. 7).

4 Metric application and case studies

In the following section, the application of the metric will be illustrated using three simple system configurations. The illustrative example will demonstrate

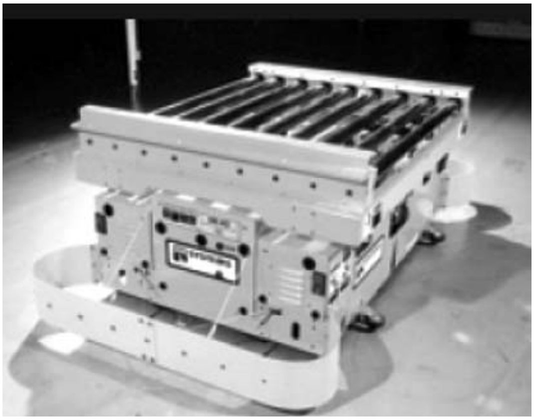


Fig. 7 AGV (http://www.hksystems.com/brochures/products/unit_load_agv.pdf)

the effects of using various components and configurations on the system complexity. In Section 4.2 the metric has been applied to a case study in order to compare feasible but different manufacturing system configurations.

4.1 Effect of machine configurations and layout

The effect of machine configuration on the complexity can be illustrated by comparing two stand-alone machines, one with a base and a single module and the other with three modules. The machine type index code and the reliability figures for each machine are needed in order to calculate their machine complexity. The type index codes for the two machines are 4341201402 and 4343201402 respectively. Their corresponding type complexity code indices which are 0.46, and 0.51, were calculated using Eq. (9). Equation (4) provides the reliability figures for each machine as 0.81 and 0.9 respectively. These numbers are then substituted in Eq. (3), and the resulting complexity indices of the single-module machine and the three-module machine are respectively 0.32 and 0.24. These results show that a machine with three identical modules (e.g. heads or spindles) introduces less complexity than a single machine module. This is because a three-module machine can continue to operate, albeit at reduced capacity, while one or two of its modules are down. When a single module machine fails it is not possible to continue production and this would result in queues and introduce operation, maintenance, re-programming, and re-setting difficulties and increase complexity.

The following basic system configurations are used to illustrate the effect of system layout patterns on the developed complexity index:

In Fig. 8, three system configurations are illustrated. A circle in each box of the above figure represents a module installed onto the machine base. All three configurations have equivalent capacity and capability. They differ in individual machine configurations and system configuration layout. Figure 8(a) represents a system consisting of three single module machines in

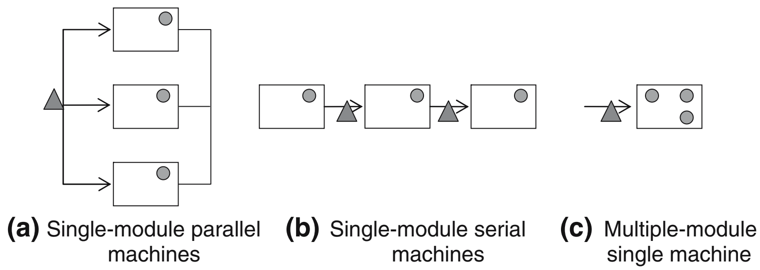


Fig. 8 Different system configurations

a parallel configuration. Figure 8(b) shows three single module machines with a serial configuration; Figure 8(c) is a stand alone machine with three modules. In configuration 8(a), three conveying modules are required to provide material handling, whereas in 8(b) and 8(c), one conveyor is sufficient. It is assumed that the machine modules used in these configurations are identical and each component's reliability is 0.9. The data and the results for these three cases are as follows: (Tables 1 and 2)

The machine complexity part for the machine in 8(c), H_{M}, shows that the system that has a single machine with three identical modules is less complex due to the elimination of the additional machine bases, and their reduced number of buffers and transporters. The difference between the serial and parallel configurations can be explained by analyzing the MHS complexity. In a parallel configuration, the failure of a conveyor does not disrupt the production; therefore, it is a less complex system.

4.2 Complexity of an engine cylinder head manufacturing system

This case study provides better details of the complexity metric, and illustrates its ability to capture the complexity of manufacturing systems. We assume that

Table 1 Data for Machine Configurations in Figure 8

Data	Systems		
	8(a) Single-module parallel machines	8(b) Single-module serial machines	8(c) Multiple-module single machine
Number of machines	3	3	1
Machine Type Index	0.46	0.46	0.51
Machine component reliability	0.9	0.9	0.9
Number of Buffers	1	2	1
Buffer Type Index	0.61	0.61	0.61
Buffer state probability	0.5	0.5	0.5
Number of Transporters	3	1	0
MHS Type Index	0.33	0.33	0
MHS Reliability	0.999	0.9	0

Table 2 Structural Complexity of the machine configurations shown in Figure 8

Complexity	Systems		
	8(a)	8(b)	8(c)
Machine - H_{M}	0.968	0.968	0.241
Buffer - H_{B1}	0.610	1.220	0.610
MHS - H_{MHS}	0.010	0.150	0
System complexity	1.588	2.338	0.851

all components that contribute to overall complexity are equally important, i.e. $w_1 = w_2 = w_3 = 1$.

The raw data for this case study such as the demand scenarios, machine concepts, production rate of each machine, and the number of stages required to finish the product is taken from Spicer's work (2002), which deals only with the economic evaluation of RMS alternatives and does not consider their complexity. In the following case study, manufacturing system configurations A1 and C1 were taken from Spicer's work and a third configuration A2 was generated based on the same set of data.

Consider an engine cylinder head manufacturing system. The processing of the cylinder head involves several operations such as boring, tapping, and drilling performed on different faces at different angle orientations. These machining operations can be performed on two different machine types: A and C. Machine type A has the following features:

1. Three axes of motion on the spindle column
2. Horizontally mounted modular spindles with automatic tool changers and the capability to have 1 to 4 spindles
3. Ability to machine one face of a cylinder head at one angle of orientation per fixture set-up.

The machine type C has additional capability to process the cylinder head by accessing multiple orientations with respect to a single face using its pivoting spindles. The machine types A and C are both reconfigurable in the sense that their capacity can be changed by adding or removing the modular spindles.

The production system that was built using machine type A requires 13 different stages in order to accomplish the set of machining tasks required for the cylinder head, whereas using machine type C requires only 6 different stages. The anticipated market demand is 1800 engines/shift, and the facility would operate at 10 h per shift.

The following three figures represent the manufacturing system configuration alternatives A1, A2, and C1 which are considered as design alternatives, and will be compared from system complexity perspective. Systems A1 and A2 consist of machines of type A and system C1 consists of machines of type C. Systems A1 and A2 have the same total number of machine modules but different number of machine bases, and both meet the capacity requirements. The system alternative A2 is generated in order to highlight the difference between using simple machines with fewer modules and using more complex machines with larger number of modules per machine.

Buffers are located between stages. The buffer types used in systems A1 and A2 are FIFO buffers with carousels holding up to 180 parts. System C1 has indexing tables with random access systems to use with AGVs. The buffer capacity is set a priori to a maximum of 180 parts. This buffer level is selected to accommodate one hour of production without disruption. Determining the necessary level of buffers requires a thorough study, which is beyond the scope of this paper.

The material handling system used in systems A1 and A2 consist of gantry robots within each stage and a conveyor for transportation between the stages. System C1 uses 5 AGVs to transport materials within and among stages (Figs. 9–11).

The above information about the structure and components of each system are used to calculate their machine, buffer and material handling system

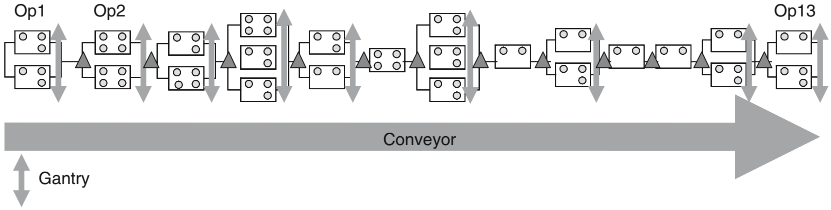


Fig. 9 Engine Cylinder Head Manufacturing System Configuration A1

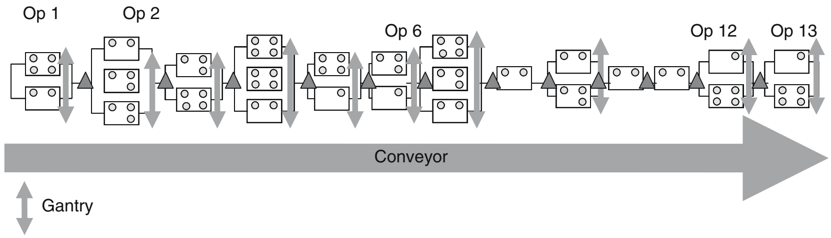


Fig. 10 Engine Cylinder Head Manufacturing System Configuration A2

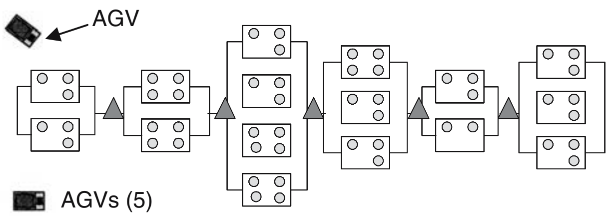


Fig. 11 Engine Cylinder Head Manufacturing System Configuration C1

Table 3 Reliability of machines with different configurations

Number of modules (n)	p_{ij2} Failure	p_{ij1} Operational
1	0.190	0.810
2	0.109	0.891
3	0.101	0.899
4	0.100	0.900

complexity using the proposed complexity metric and indices. In this case study, it is assumed that each component's reliability is 0.9. The probability of operational or failure states for a machine with n modules can be calculated using Eq. (4). The following table represents these probabilities (Table.3).

According to the complexity code, machines type A and C have the following type representation codes (Table 4):

Using Eq. (9), machines A and C have a type complexity index of 0.53 and 0.64 respectively.

4.2.1 Buffer complexity

Since there is only one product to be manufactured in all systems, A1, A2, and C1, the buffer complexity component H_{B2} becomes equal to 0. The evaluation of the system configuration alternatives is an early design stage activity; therefore, there is normally no data available to predict the states of the buffers. As a worst-case scenario, it is assumed that each buffer state (empty, non-empty) has equal probability of occurrence.

4.2.2 Material handling system complexity

The material handling systems in configuration A1 and A2 consist of nine and ten gantries respectively for moving parts within the stages. A uni-directional conveyor is used to move the parts from one stage in the system to the next. Since the process plan requires a uni-directional parts flow, the failure of any MHS equipment would result in the disruption of the overall production line. Assuming that all elements in the material handling system should be operational for the entire system to run, the reliability of the material handling system in configuration A1 and A2 is:

$$p_{\mathrm{MHS\_A1}} = 0.9^{10} = 0.35 \tag{10}$$

$$p_{\mathrm{MHS\_A2}} = 0.9^{11} = 0.31 \tag{11}$$

System C1 uses 5 AGVs with a free routing capability. Since the AGVs have this feature, the failure of one AGV does not disrupt the production

Table 4 Classification code strings for machine types A and C

	Machine A	Machine C
Machine type code	4344201402	4444202442

system since it can be replaced or the others can be re-routed to accommodate the failure. The material handling system's reliability for the system C1 is equal to:

$$p_{\mathrm{MHS\_C1}} = 1 - 0.1^5 = 0.999 \quad (12)$$

As defined in Eq. (9) and Section 3.3.3, the complexity type code m for material handling systems in A1, A2, and C1 are 332, 332, and 525 respectively. Equation (9) has been used to convert the codes to the corresponding indices to be used in Eq. (8). These indices are 0.53 for system A1 and A2 and 0.80 for system C1.

The system structural complexity results for the three different system configurations show that using multi-module machines reduces complexity compared to using single module machines. The comparison of systems A1 and A2 reveals that the machine complexity increases while the total number of modules in both systems remains equal. The reason for this increase is due to the increased number of machine bases, which means having additional equipment to be managed, programmed, or controlled.

System C1's machine complexity is less than A1 and A2's machine complexity due to the fact that machine concept C is more capable than machine concept A. The use of more capable machines reduces the number of stages to accomplish the required processing tasks. The percentage reduction in number of machines from 24 to 18 (25%) results in the reduction of machine complexity by (20%). This is a result of using more capable machine type in system C1, which is reflected on the equations via the machine type code indices.

We should also mention that using more capable type of machines reduces the overall complexity by eliminating the number of buffers required in the system. This would result in fewer resources to manage and hence it reduces complexity.

The results in Table 5 show that one of the major contributors to systems complexity is the material handling. The material handling system complexity in system A1 and A2 is much higher than system C1's as a result of using functionally serial equipment. The failure in any material handling system component of configuration A1 and A2 would result in a halt in the production. System C1 has the ability to continue to produce with reduced capacity in case of failure in one of the MHS elements. Using individual, more flexible material handling elements allows the system to continue operation with the least disruption.

5 Discussion and conclusions

In this paper, the existing approaches for measuring manufacturing systems complexity have been reviewed and a new approach was proposed to assess the complexity of a manufacturing system configuration. A comprehensive

Table 5 Engine cylinder head manufacturing systems configuration complexity

System characteristics	System configuration		
	A1	A2	C1
# Machine bases	24	26	18
# Modules	70	70	60
# Buffers	12	12	5
# MHS elements	9 + 1	10 + 1	5
Machine type index	0.53	0.53	0.64
Buffer type index	0.61	0.61	1
MHS type index	0.53	0.53	0.8
Machine complexity H_{M}	6.11	7.11	4.86
Buffer complexity H_{B}	7.33	7.33	5
MHS complexity H_{MHS}	4.98	5.27	0.05
System complexity	18.42	19.71	9.91

structural complexity metric has been developed which takes into consideration the main components of a manufacturing system such as machines, buffers, and material handling equipment, and their relationship or system structure, for a multi-product environment. The proposed method can be used to compare systems the components of which may be different. For example, a system that contains machines and transporters but does not include buffers may be compared with one that has all three types of modules using the developed complexity metric where the term that accounts for the complexity arising from the presence of buffers will be eliminated for the former. The manufacturing systems may be different but their comparison using the proposed metric is still valid and accounts for the difference between them in terms of their structural complexity as explained above. This metric provides insight into the inherent complexity of system components and structure, and the manageability of manufacturing systems configurations. It can be used to assist in selecting a less complex system at the early design stages. The various types and technologies of buffers, machines, and MHS can be expressed quantitatively using the type index based on a newly developed manufacturing systems classification code. The proposed entropy-based metric is capable of incorporating the amount of information, as well as the diversity of information inherent in complex systems using the classification codes. It also has the ability to detect the differences in structural, time-independent complexity between a serial and parallel configuration as well as simple and multi-purpose machines. While this metric has been developed for manufacturing systems involving machining operations, it is equally applicable to other types of manufacturing systems, such as assembly lines. The application of the developed manufacturing systems complexity metric was illustrated with several examples. Its use becomes even more important for larger manufacturing systems where the effect of changes in system structure and configuration, its modules/components and their relationships is less intuitive.

The results of the case studies show that using more capable machines in a manufacturing system would reduce the overall complexity by decreasing the required number of machines. In addition, using more capable machines decreases complexity by reducing the number of required buffers. The metric shows that the use of AGVs as MHS creates free routing, which results in a less complex material handling system since the failure of a transporter does not disrupt the production. However, using more capable equipment may also mean higher initial investment; therefore, there should be a trade-off at the design stage between the complexity level and the required investment.

The proposed structural complexity metric was shown to be sensitive to changes in manufacturing system configuration components and their inter-relationships. Its use would be beneficial in the early systems design synthesis and analysis in considering the relative merits of reconfigurable and flexible manufacturing systems (ElMaraghy 2005).

The relationship between complexity and overall cost of a manufacturing system, and the identification of complexity as a source of added cost in the initial manufacturing system as well as its operation and management, are issues that merit further research.

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