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ORIGINAL ARTICLE

A model for measuring complexity of automated and hybrid assembly systems

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Abstract The demand for delivering product variety has been increasing. Increased product variety caused by product customization, personalization, evolution and changes in their manufacturing systems. Variety allows manufacturers to satisfy a wide range of customer requirements, but it can also be a major contributing factor to increased complexity of assembly. Complexity is generally believed to be one of the main causes of the present challenges in manufacturing systems such as lengthy and costly design processes, higher life cycle costs and the existence of numerous failure modes. Complex assembly systems are costly to implement, run, control and maintain. Assessing complexity of assembly helps guides designers in creating assembly-oriented product designs and following steps to reduce and manage sources of assembly complexity. On the other hand, reducing complexity of assembly helps lower assembly cost and time, improves productivity and quality and increases profitability and competitiveness. The complexity of assembly should be assessed by considering both products and their assembly systems. In this paper, a structural classification coding scheme has been used to measure assembly systems complexity. It considers the inherent structural complexity of typical assembly equipment. The derived assembly systems complexity accounts for the number, diversity and information content within each class of the assembly system modules. A domestic appliance drive assembly system is used to demonstrate the use of the classification code to calculate the assembly system complexity. The developed complexity metrics can be used by designers as decision support tools to compare and rationalize various automated assembly systems alternatives and select the design that meets the requirements while reducing potential assembly complexity and associated cost.

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Nomenclature

N_j	Total number of items within an assembly equipment class type j
n_j	Distinct number of items within a class type j
A_j	Radar plot total area of a class type j
a_j	Radar plot shaded area of a class type j
C_i	Normalized code value of digit i
I_j	Complexity index of a class type j
$\bar{I}_j$	Average complexity index of a class type j
C_j	Complexity of a class type j
C_{sys}	Total complexity of all classes within an assembly system
w_j	Relative weight of class type j

Subscripts

i	Digit number
j	Class type j = M, MHS, B
M	Machine
MHS	Material handling system
B	Buffer

1 Introduction

The competitive nature of companies emphasizes the importance of product development. Many manufacturing and assembly challenges emerged due to the increase of product variety caused by product evolution, increased customization and changes in their manufacturing systems [1, 2]. The number of products being offered by companies to include almost every configuration their target market might want has grown. As a result, the variety of products has increased greatly. In a typical automobile assembly plant, the number of different vehicles being assembled can reach a large number of build-combination options. Such product variety undoubtedly presents enormous difficulties in the design and operation of these products' assembly systems. Assembly process greatly affects the product's final quality and cost [3]. Assembly of manufactured goods accounts for over 50% of total production time and for 20% of the total unit production cost. Typically, about one third of a manufacturing company's labour is involved in assembly tasks. In the automotive industry, 50% of the direct labour costs are due to assembly. These statistics indicate the relative importance of assembly and point to the potential savings attainable by improving the assembly technology and systems [4]. Assembly is unique compared to other methods of manufacturing due to the possibility of manual operations. It is complex both at the micro- and macro-levels [5].

1.1 Complexity

Complexity is seen as a core challenge for present and future manufacturing companies. Complexity cannot just be made simple and will not disappear in the near future. Defining the meaning of complexity itself is difficult. The definitions that have been offered are either only applicable to a very restricted domain or are so vague that they are almost meaningless. Concepts of complexity have been considered in disciplines including psychology, physics, management and biological and information sciences [6, 7]. Having an accurate definition of complexity is a necessary condition for being able to measure and manage it. In the context of manufacturing processes, assembly costs and product quality, complexity plays a very important role in the achievement of the best product design that considers both assembly planning and the selection of the most suitable manufacturing process [7].

Manufacturing systems are a complicated combination of tools, machines, computers, human workers and managers. Modern manufacturing systems are becoming increasingly complex. In an automotive industry, it might take very long time to accurately model hundreds of production lines for initial simulation studies [8]. Complex systems share certain features, such as having a large number of elements, having high dimensionality and representing an extended space of possibilities. 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 [9, 10]. The complexity of a physical system can be characterized in terms of its static structure or dynamic behaviour. Static, or structural, complexity accounts for the inherent characteristics of the system structure and the relationships among its elements, along with the variety of its components and the interactions between them. Dynamic complexity deals with a system's operation characteristics and the unpredictability of its behaviour over a time period [7, 9]. The concept of complexity is relative to two dimensions: uncertainty and time. Uncertainty may be due to lack of information and/or the nature of the interaction among the system components and time-dependent decisions and operations.

Despite the lack of a unified formal definition of complexity, it is accepted that modern engineering systems are becoming more complex, large systems have relatively high complexity and modular systems have lower complexity [6]. The functionality of a system is proportional to its complexity—more complex systems normally perform more functions but at a price. Increased complexity has presented difficulties in operation and management levels, negatively affecting quality and productivity [11, 12]. Therefore, it is becoming important to study and measure complexity.

1.2 Complexity metrics

Research has been conducted to measure and quantify complexity using either an entropy/information content approach [9, 13–16] or heuristics and indices [17–19]. The concept of information, originally developed by Shannon [20], which expresses uncertainty about an information source in terms of probability, it is often used in literature. The entropy/information approach produces a single number representing complexity that facilitates the comparison between several system options; however, the assumption of variables independency may not always be true in real systems. Heuristic approaches use metrics based on knowledge and personal judgement and they are easy to apply to real systems. However, the extent to which certain metrics reflect the actual system complexity can be argued. Also, they are usually not universally applicable to different types of systems. The axiomatic design approach adopts both heuristic and entropic methods. Suh [16] defines complexity using axiomatic design as a measure of uncertainty in achieving the desired functional requirements. This complexity is related to the information content defined as a logarithmic function of the probability of success of design parameters in meeting the specified functional requirements. W. ElMaraghy and Urbanic [17] presented a methodology to assess product and process complexity and their interrelations in a systematic manner and derived product and process complexity indices. They used three basic elements of complexity drivers: (a) the absolute quantity of information, (b) the diversity of information and (c) the information content. The information content corresponds to the effort to produce a machining feature within a part. Their model was applied to measure product and process complexity in machining. This complexity model was also extended by W. ElMaraghy and Urbanic [18] to consider complexity in machining at the operational level by including some aspects of cognitive complexity related to operators perception in manual tasks.

H. ElMaraghy [21] developed a novel manufacturing system structure classification code (SCC), which captures the inherent structural and operation related complexity due to the characteristics of manufacturing system modules and layout configuration. It consists of fields representing equipment, such as machines, buffers and transporters and the type of system layout. Each field contains a string of digits, the value of which depends on the degree of structure, control, programming and operation complexity of these entities. The resulting code string is similar to a biological DNA identifier for the system elements [22]. It accounts for the complexity inherent in the various modules in the manufacturing system. Kuzgunkaya and H. ElMaraghy [9] used that structure classification code in developing a metric for assessing the inherent structural complexity of manufacturing system modules and configurations by virtue of their design characteristics and applied it to machining systems for illustration. This structural system complexity metric incorporates the quantity of information using an entropy formulation combined with the system structure code. Later, H. ElMaraghy et al. [23] extended the original code to include assembly-specific structure features of various assembly equipment.

Complexity has been also defined in an analytical form for manufacturing systems as a measure of how product variety can complicate the production process. MacDuffie et al. [24] used multiple product complexity measures, derived from the statistical analysis of productivity of 70 auto-assembly plants worldwide, to test the impact of product variety on productivity and quality. Similar work was done by Fisher and Ittner [25] whose research was performed from a managerial perspective. They used empirical tests of data from an automotive assembly plant and simulation analyses of a generic auto-assembly line to examine the impact of product variety on automobile assembly plant performance. Martin and Ishii [19] developed metrics to measure and compare the cost of product variety. They developed three indices: parts commonality index, differentiation point in manufacturing processes index and setup cost index. The cost related to increased product variety can be reduced by increasing the commonality of parts, postponing the differentiation point and lowering setup cost. Fujimoto et al. [26] introduced systematic information entropy-based methodology to strategically manage product variety by synthesizing product-based and process-based variety measures. Sarkis [27] studied the productivity of flexible manufacturing systems as they become more complex. Complexity was measured by the number of numerically controlled machine tools and industrial robots in the system. In flexible manufacturing system (FMS), larger number of numerically controlled machine tools and industrial robots require more operation and control efforts including scheduling and transportation, which may lead to higher complexity. Productivity was analysed by using data envelope analysis where the inputs consist of complexity measures and the outputs consist of process/inventory reduction, lead time reduction, unit cost reduction and personnel reduction measures. This complexity analysis may not be generally applicable to systems other than FMS.

2 Assembly machines and systems

Most assembly machines and systems are designed for a particular product or a family of products. Basic components of assembly machines include assembly heads and devices, work holding fixtures, transfer and/or indexing mechanisms, feeders and orienting devices. In addition to their main functions, assembly machines and systems also include means for easy and rapid removal of jammed parts or defective assemblies. Safety, noise control and environmental protection devices are also essential. Sufficient space is normally provided around the system for material handling and storage as well as for access by maintenance and repair personal.

There are three main assembly methods: manual, automatic and hybrid assembly. Manual assembly is characterized by operations performed manually, with or without the aid of tools, and has relatively low productivity and high product variety. One advantage of manual assembly is the volume flexibility which can be controlled by extending or shortening the daily operations schedule or adjusting the number of workers. Additionally, workplace components can be reused easily [28]. Automatic assembly, often referred to as fixed or hard automation, uses indexing tables and parts feeders. Soft automation incorporates the use of programmable assembly machines and robots in a single or a multi-station robotic assembly cell/system with all activities simultaneously controlled and coordinated by a programmable logic controller or a computer [29]. Flexible automated assembly systems include the basic process elements and transfer modules. The hardware modules used to conduct operations such as fastening, welding or testing are inserted into the automated stations manually using a loading platform, or automatically, whereas data and energy are transferred via plug-in connections [28]. The mobility of the process modules is advantageous since system modifications can usually be completed in less than an hour or sometimes a few minutes. Capital cost investment can be incremental and grows or shrinks with the varying demand during the product life span. Hybrid assembly systems refer to combined automated and manual workstations where the most favourable output ratio is determined by adjusting the degree of automation for individual assembly operations. Hybrid assembly systems are characterized by production rates and product variations between those for the manual and automated assembly systems. One advantage is their flexibility regarding the number of pieces, which can be controlled by changing the number of assembly workers on the manual workstations. Additionally, the initial degree of automation can be adapted to changes in the production rate during the entire service life using a number of extension stages. Two types of flow are found in single stations: set-wise and one-piece flow. In single station assembly with set-wise assembly flow, the first part is assembled for the entire product run one after the other. Then the second part is assembled, and so on until the last part is assembled, completing the product assembly of the whole lot. Single station assembly, operating according to the one-piece-flow principle, is useful for large number of parts and product variants assembled in small lot sizes. If the product variants and product quantities are high, then the multi-station assembly according to the one-piece-flow principle would be more suitable.

3 Manufacturing systems structure classification code

Coding and classification were originally used for controlling design versions and material storage and retrieval. However, with the development of work statistics and group technology, the use of coding and classification has spread into production planning and control and the selection of components for group machining [30, 31]. Also, advances in the application of computers have extended the use of coding and classification especially for information storage and retrieval [32, 33]. Coding and classification is a method of organizing knowledge by sorting and analysing information and grouping similar features, facts and elements. Coding refers to the process of assigning symbols to entities. The symbols in the code could be all numeric, all alphabetic or a combination of both types. For parts coding, the symbols represent the attributes of parts which may later be used for similarity analysis and applications such as forming families of parts with similar attributes or retrieving and modifying process plans and computer numerical control programmes. The process of coding is preceded by classification for each critical attribute. Classification refers to categorization of parts into part families.

Classification and coding systems were originally developed for manufactured parts. However, equivalent coding and classification systems for manufacturing systems did not exist until the development of the SCC system by H. ElMaraghy [21]. The original SCC manufacturing structural classification coding system was introduced to classify the various types of equipment in a manufacturing system and their layout. The equipment classification code consists of the following major classes of entities: (1) machines to carry out the manufacturing processes, (2) buffers to ensure the continuous supply of parts, (3) material handling equipment to transfer parts between machines and (4) operators for complementary manual tasks, system operations and supervisory tasks. There can be a large variation in the type of system entities to respond to changing production requirements. The number of such resources and variety within a class of entities add to the overall quantity of information required to plan, operate and control them and the whole system. The first code field describes the equipment type. The control, programmability and operation characteristics, which are common to all equipment types, are described in the second, third and the fourth code fields, respectively. The buffers and transporters codes are structured similarly. The layout classification code consists of four fields: (1) system type, (2) system control, (3) programming and (4) operation. The first field describes the layout type of the manufacturing system including its overall shape, the characteristics of the flow patterns identifying the layout segments that connect the pieces of equipment, the type of flow as well as the number and type of junctions that control the flow between various system segments. The developed SCC code is a chain type poly-code with independent meaning of all digits. Each field contains a string of digits; the value of each digit depends on the degree of complexity of the structure, control, programming and operation of the corresponding entities. The generated code string is similar to a biological DNA identifier for the system characteristics. The value of any digit in the code string reflects the degree of structural complexity of the feature it represents manifested by the amount and variety of information required to use, operate, programme, control and interact with it. The higher the digit value, the more complex is the corresponding feature. The values defined in the coding system are based on available data and experience in the field. The resulting equipment codes are useful for the purpose of comparing different manufacturing systems [21].

4 Assembly systems structure classification code

The original equipment SCC [21] is extended [23] to include the assembly-specific structural features of typical equipment used in product assembly systems. Some of the original code digits have been re-grouped and extended. The layout classification scheme remains unchanged and is not the focus of this work. The extended classification code consists of seven digits for describing machine type, seven digits for describing handling equipment and four digits for describing buffers. An additional nine digits for the control, programming and operation are common for all equipment. Thus, the maximum number of the equipment code digits is 16.

The various digits are described in Tables 1, 2 and 3 and annotated in Tables 17, 18, 19, 20, 21 and 22 of "Appendix 1".

Table 1 Machine classification code

#	Machine CC	Description	Value	Maximum value	Normalized value
1	Structure	Fixed	1	3	1/3
		Modular	2		2/3
		Changeable	3		3/3
2	Axes of motion	*N*	*N*	6	*N*/6
3	Workheads	*N*	*N*	2[a]	*N*/2
4	Spindles	*N*	*N*	2[b]	*N*/2
5	Tools	Fixed	1	2	1/2
		Changeable	2		2/2
6	Tool magazine	None	1	3	1/3
		Fixed	2		2/3
		Changeable	3		3/3
7	Pin fixtures	Fixed	1	2	1/2
		Moving	2		2/2
	Controls CC				
8	Mode	Manual	1	2	1/2
		Programmable	2		2/2
9	Type	Non-adaptive	1	2	1/2
		Adaptive	2		2/2
10	Access	Open	1	3	1/3
		Limited	2		2/3
		Closed	3		3/3
11	Structure	Fixed	1	3	1/3
		Modular	2		2/3
		Reconfigurable	3		3/3
	Programming CC				
12	Mode	Manual	1	2	1/2
		Programmable	2		2/2
13	Difficulty	Low	1	3	1/3
		Medium	2		2/3
		High	3		3/3
	Operation CC				
14	Mode	Manual	1	3	1/3
		Semi-automated	2		2/3
		Fully automated	3		3/3
15	Power	Un-powered	1	2	1/2
		Powered	2		2/2
16	Fault detection	Manual	1	2	1/2
		Automated	2		2/2

[a] The maximum number of *N* is assumed as two workheads

[b] The maximum number of *N* is assumed as two spindles

Table 2 Handling equipment classification code

#	MHS CC	Description	Value	Maximum value	Normalized value
1	Type	Conveyor	1	7	1/7
		Monorail	2		2/7
		Forklift trucks	3		3/7
		AGV	4		4/7
		Cranes and Gantries	5		5/7
		Robot	6		6/7
		Feeder	7		7/7
2	Structure	Fixed	1	2	1/2
		Reconfigurable	2		2/2
3	Motion	Uni-directional, synchronized	1	4	1/4
		Uni-directional, asynchronized	2		2/4
		Bi-directional, synchronized	3		3/4
		Bi-directional, asynchronized	4		4/4
4	Path	Fixed	1	2	1/2
		Variable	2		2/2
5	Parts holders	None	1	4	1/4
		Pallet	2		2/4
		Fixture	3		3/4
		Gripper	4		3/4
6	Part types	Single	1	2	1/2
		Multiple	2		2/2
7	Parts orientation	Passive	1	2	1/2
		Active	2		1/3
	Controls CC				
8	Mode	Manual	1	2	1/2
		Programmable	2		2/2
9	Type	Non-adaptive	1	2	1/2
		Adaptive	2		2/2
10	Access	Open	1	3	1/3
		Limited	2		2/3
		Closed	3		3/3
11	Structure	Fixed	1	3	1/3
		Modular	2		2/3
		Reconfigurable	3		3/3
	Programming CC				
12	Mode	Manual	1	2	1/2
		Programmable	2		2/2
13	Difficulty	Low	1	3	1/3
		Medium	2		2/3
		High	3		3/3
	Operation CC				
14	Mode	Manual	1	3	1/3
		Semi-automated	2		2/3
		Fully automated	3		3/3
15	Power	Un-powered	1	2	1/2
		Powered	2		2/2
16	Fault detection	Manual	1	2	1/2
		Automated	2		2/2

Table 3 Buffer classification code

#	Buffers CC	Description	Value	Maximum value	Normalized value
1	Type	Magazines	1	4	1/4
		Indexing tables	2		2/4
		Carousels	3		3/4
		AS/RS	4		4/4
2	Part types	Single	1	2	1/2
		Multiple	2		2/2
3	Access	FIFO	1	3	1/3
		LIFO	2		2/3
		Random access	3		3/3
4	Location	With machine	1	3	1/3
		Separate	2		2/3
		Central	3		3/3
	Controls CC				
5	Mode	Manual	1	2	1/2
		Programmable	2		2/2
6	Type	Non-adaptive	1	2	1/2
		Adaptive	2		2/2
7	Access	Open	1	3	1/3
		Limited	2		2/3
		Closed	3		3/3
8	Structure	Fixed	1	3	1/3
		Modular	2		2/3
		Reconfigurable	3		3/3
	Programming CC				
9	Mode	Manual	1	2	1/2
		Programmable	2		2/2
10	Difficulty	Low	1	3	1/3
		Medium	2		2/3
		High	3		3/3
	Operation CC				
11	Mode	Manual	1	3	1/3
		Semi-automated	2		2/3
		Fully automated	3		3/3
12	Power	Un-powered	1	2	1/2
		Powered	2		2/2
13	Fault detection	Manual	1	2	1/2
		Automated	2		2/2

4.1 Example

Figure 1 shows a machine typically used in assembly systems to assemble washer and screw together automatically. It is equipped with safety movement and detective sensors, to protect the operator and machine from damage. The feeding and assembling points are equipped with sensors. The machine stops automatically if it runs out of the parts. The code digit values for this machine are shown in Table 4, and the code string is shown in Table 5.

4.2 Complexity index for assembly system modules

The used code is indicative of the inherent structural equipment, programming, operation and control complexity. However, an index is proposed for each class of equipment to incorporate more factors than those included in the SCC code as follows.

The SCC code strings of digits for each piece of equipment in the assembly system are reduced to a single number which indicates the information content of equipment. This can be done using many methods, such as the arithmetic mean or median. Such methods are easy to apply but they are greatly affected by data outliers. A more robust method is to represent the code string values graphically on a radar plot in the same order as they appear in the code string which is a fixed sequence of digits determined by the design of the code.

For each piece of equipment in each of the three equipment classes, the various code digits, normalized by the corresponding maximum value of each digit, are plotted in a radar plot as shown in Fig. 2. A complexity index is defined as the ratio between shaded area and the total area of the radar plot (full circle). Larger shaded area indicates a higher complexity index. The shaded area of each radar plot can be calculated as the summation of individual triangles:

$$\begin{aligned} a_{\mathrm{M}} &= \frac{1}{2}\left[(C_1 \times C_{16}) + \sum_{i=1}^{i=15}(C_i \times C_{i+1})\right]\sin\left(\frac{360}{16}\right) \\ a_{\mathrm{MHS}} &= \frac{1}{2}\left[(C_1 \times C_{16}) + \sum_{i=1}^{i=15}(C_i \times C_{i+1})\right]\sin\left(\frac{360}{16}\right) \\ a_{\mathrm{B}} &= \frac{1}{2}\left[(C_1 \times C_{13}) + \sum_{i=1}^{i=12}(C_i \times C_{i+1})\right]\sin\left(\frac{360}{13}\right) \end{aligned} \tag{1}$$

where a_{M}, a_{MHS} and a_{B} are the shaded areas of the radar plots of machine, material handling and buffer equipment, respectively. C_i is the normalized code string digit value on the radial axis of digit i for each radar plot, e.g., in Fig. 3a i=2, C_2=1.

For a given assembly equipment, the shaded area of its radar plot is normalized by dividing it by the maximum radar chart area given by:

$$\begin{aligned} A_{\mathrm{M}} &= (16/2)\sin(360/16) \\ A_{\mathrm{MHS}} &= (16/2)\sin(360/16) \\ A_{\mathrm{B}} &= (13/2)\sin(360/13) \end{aligned} \tag{2}$$

where A_{M}, A_{MHS} and A_{B} are the total radar plot areas for machine, material handling and buffer equipment, respectively.

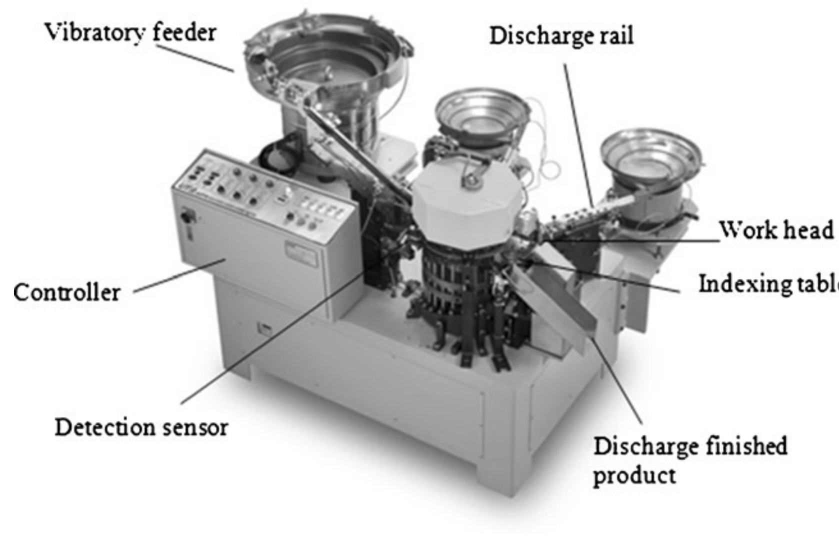


Fig. 1 M-type washer assembly machine [34]

Then, the complexity index, I, for each class of equipment is calculated by dividing the shaded area by the total radar chart area. For example, for an assembly machine represented by a 16-digit code string:

$$I_{\mathrm{M}} = \frac{a_{\mathrm{M}}}{A_{\mathrm{M}}} = \frac{1}{16}\left[(C_1 \times C_{16}) + \sum_{i=1}^{i=15}(C_i \times C_{i+1})\right] \quad (3)$$

Similarly, for material handling and buffer devices represented by a 16- and 13-digit code strings, respectively:

$$\begin{aligned} I_{\mathrm{MHS}} &= \frac{a_{\mathrm{MHS}}}{A_{\mathrm{MHS}}} = \frac{1}{16}\left[(C_1 \times C_{16}) + \sum_{i=1}^{i=15}(C_i \times C_{i+1})\right] \\ I_{\mathrm{B}} &= \frac{a_{\mathrm{B}}}{A_{\mathrm{B}}} = \frac{1}{13}\left[(C_1 \times C_{13}) + \sum_{i=1}^{i=12}(C_i \times C_{i+1})\right] \end{aligned} \quad (4)$$

For the M-type washer assembly machine shown in Fig. 1, the radar plot is shown in Fig. 3. The shaded and total areas of the radar plot are 1.228 and 3.061, respectively. Thus, the complexity index of this machine is:

Table 4 Classification coding for the M-type washer assembly machine

	Description	Digit value	Maximum value	Normalized value
Machine CC				
Structure	Modular	2	3	0.667
N axes of motion	*N*	1	6	0.167
N workheads	*N*	1	2	0.500
N spindles	*N*	1	2	0.500
Tools	Fixed	1	2	0.500
Tool magazine	None	1	3	0.333
Pin fixtures	Fixed	1	2	0.500
Controls CC				
Mode	Programmable	2	2	1.000
Type	Open loop	1	2	0.500
Access	Limited	2	3	0.667
Structure	Fixed	1	3	0.333
Programming CC				
Mode	Manual	1	2	0.500
Difficulty	Low	2	3	0.667
Operation CC				
Mode	Fully automated	3	3	1.000
Power	Powered	2	2	1.000
Fault detection	Automated	2	2	1.000

Table 5 M-type washer assembly machine code string

Field #1							Field #2				Field #3		Field #4		
2	1	1	1	1	1	1	2	1	2	1	1	2	3	2	2

M − type washer assembly machine complexity index

$$= \frac{a_{\mathrm{M}}}{A_{\mathrm{M}}} = \frac{1.228}{3.061} = 0.401$$

The aggregated code for a piece of equipment represents the information content defined by its type, controls, programming and operation fields and is calculated for each piece of equipment within the assembly system. It is used together with the diversity and the amount of information to obtain a complexity index for each piece of equipment then a complexity measure for the whole assembly system complexity as described in the section below.

Individual pieces of equipment, in all three classes, are analysed to generate the corresponding SCC codes and a complexity index for each is calculated. The resulting indices are then used to calculate the complexity of each class of assembly equipment. The resulting complexity values of the three classes of equipment are then used to calculate the assembly system complexity as explained in the next section.

4.3 Equipment complexity

In addition to the information content defined in the previous section and represented by the three complexity indices "I_{M}, I_{MHS}, I_{B}", the diversity of information and amount of information are incorporated to calculate the overall equipment complexity by adapting the complexity model proposed by W. ElMaraghy and Urbanic [17].

The assembly machine complexity is represented by:

$$C_{\mathrm{M}} = \left(\frac{n_{\mathrm{M}}}{N_{\mathrm{M}}} + \bar{I}_{\mathrm{M}}\right)[\log_2(N_{\mathrm{M}} + 1)] \qquad (5)$$

where C_{M} is the machine complexity, N_{M} is the total number of assembly machines in a system (an indicator of amount), n_{M} is the number of unique assembly machines (an indicator of diversity) and $\bar{I}_{\mathrm{M}}$ is the average complexity index of the N_{M} assembly machines (an indicator of content).

Similarly, the material handling equipment complexity is represented by:

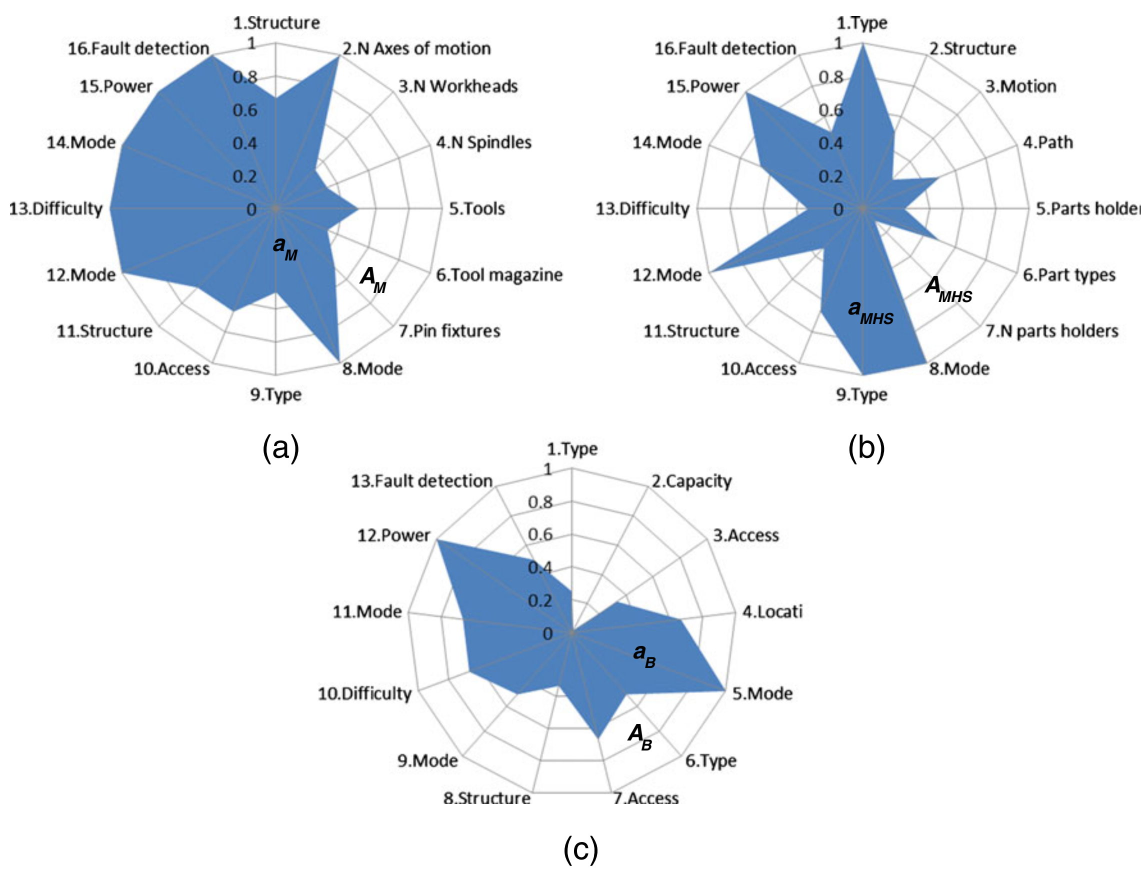


Fig. 2 Radar plot SCC digits representation: **a** machine, **b** MHS, **c** buffer

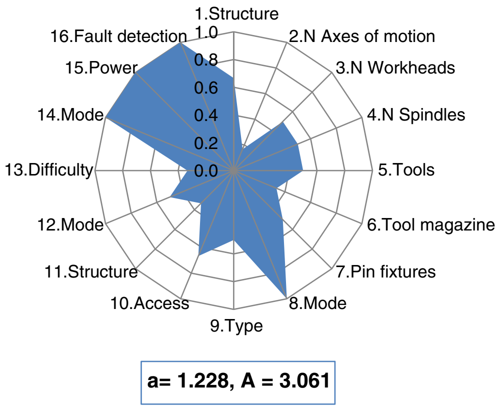


Fig. 3 Radar plot of M-type washer assembly machine

$$C_{\mathrm{MHS}} = \left(\frac{n_{\mathrm{MHS}}}{N_{\mathrm{MHS}}} + \overline{I}_{\mathrm{MHS}}\right)[\log_2(N_{\mathrm{MHS}} + 1)] \quad (6)$$

where C_{MHS} is the material handling complexity, N_{MHS} is the total number of material handling equipment, n_{MHS} is the number of unique material handling equipment and $\overline{I}_{\mathrm{MHS}}$ is the average complexity index of the N_{MHS} material handling equipment.

The buffer equipment complexity is represented by:

$$C_{\mathrm{B}} = \left(\frac{n_{\mathrm{B}}}{N_{\mathrm{B}}} + \overline{I}_{\mathrm{B}}\right)[\log_2(N_{\mathrm{B}} + 1)] \quad (7)$$

where C_{B} is the buffer equipment complexity, N_{B} is the total number of buffer equipment, n_{B} is the number of unique buffer equipment, $\overline{I}_{\mathrm{B}}$ is the average complexity index of the N_{B} buffer equipment.

The first terms of the right-hand side of Eqs. 4, 6 and 7: $(n_{\mathrm{M}}/N_{\mathrm{M}})$, $(n_{\mathrm{MHS}}/N_{\mathrm{MHS}})$ and $(n_{\mathrm{B}}/N_{\mathrm{B}})$ represent the diversity of information of machines, handling equipment and buffer equipment, respectively. The second terms, $(\overline{I}_{\mathrm{MHS}})$ and $(\overline{I}_{\mathrm{B}})$ represent the information content of machines, handling equipment and buffer equipment, respectively. The terms: $[\log_2(N_{\mathrm{M}} + 1)]$, $[\log_2(N_{\mathrm{MHS}} + 1)]$ and $[\log_2(N_{\mathrm{B}} + 1)]$ represent the quantity of information of machines, handling equipment and buffer equipment, respectively.

The proposed metric for assembly system complexity is different from the one developed by W. ElMaraghy and Urbanic [17] in the method of calculating the information content index and the inclusion of aggregated individual system components complexity indices to obtain an overall measure of assembly system complexity as shown in the following section.

4.4 System complexity model

After calculating the complexities of the assembly machines, material handling and buffer equipment, the assembly system complexity is represented by:

$$C_{\mathrm{system}} = w_1 C_{\mathrm{M}} + w_2 C_{\mathrm{MHS}} + w_3 C_{\mathrm{B}} \quad (8)$$

where C_{system} is the assembly system complexity and C_{M}, C_{MHS}, C_{B} are machine, material handling and buffer equipment complexities, respectively. The w_1, w_2, w_3 are weights representing the relative importance of the complexity of the three classes. These weights would be determined based on the users experience and desire to emphasize certain components of the system. They are set at 1 in the remainder of this work as an indication of equal importance of all three classes of equipment in the system. The methodology to calculate system complexity is summarized as follows:

1. Decompose the system equipment into three classes: machines, handling equipment and buffer equipment.
2. Specify the characteristics of each piece of equipment in each class as described in Tables 1, 2 and 3.
3. Generate the classification code string for each piece of equipment.
4. Calculate the complexity index for each piece of equipment as defined by Eqs. 3 and 4, i.e. I_{M}, I_{MHS}, I_{B}.
5. Calculate the average complexity index of the three classes of equipment, i.e. $\overline{I}_{\mathrm{M}}, \overline{I}_{\mathrm{MHS}}, \overline{I}_{\mathrm{B}}$.
6. Count the total number of equipment within each class, i.e. N_{M}, N_{MHS}, N_{B}.
7. Count the number of unique equipment within each class, i.e. n_{M}, n_{MHS}, n_{B}.
8. Calculate the complexity of each class of equipment as defined by Eqs. 4, 6 and 7, i.e. C_{M}, C_{MHS}, C_{B}, respectively.
9. Define the relative importance of each class, i.e. w_1, w_2, w_3.
10. Calculate the overall assembly system complexity as defined by Eq. 8.

5 Case study

5.1 Assembly of domestic appliance drive

Figure 4 shows the layout of assembly equipment used for assembling the domestic appliance drive shown in Fig. 5. A SCARA robot is placed in the centre of the assembly equipment for the completion of the automatic operations. Gripping points G1 to G9 are positioned within the working envelop of the robot. The cylindrical pins and spring nuts are passively oriented by small vibratory bowl feeders and delivered to the gripping points via discharge rails. A large bowl feeder with active orientation devices is used for the gearwheels. The bearing ring and thrust washer are drawn from chute magazines and fed to the gripping points. The drive shaft, drive, stepped shaft and fan wheel are placed manually on feed rails or double-belt systems and transported to the gripping points. A circular table with 18-work piece carriers is positioned upstream of the

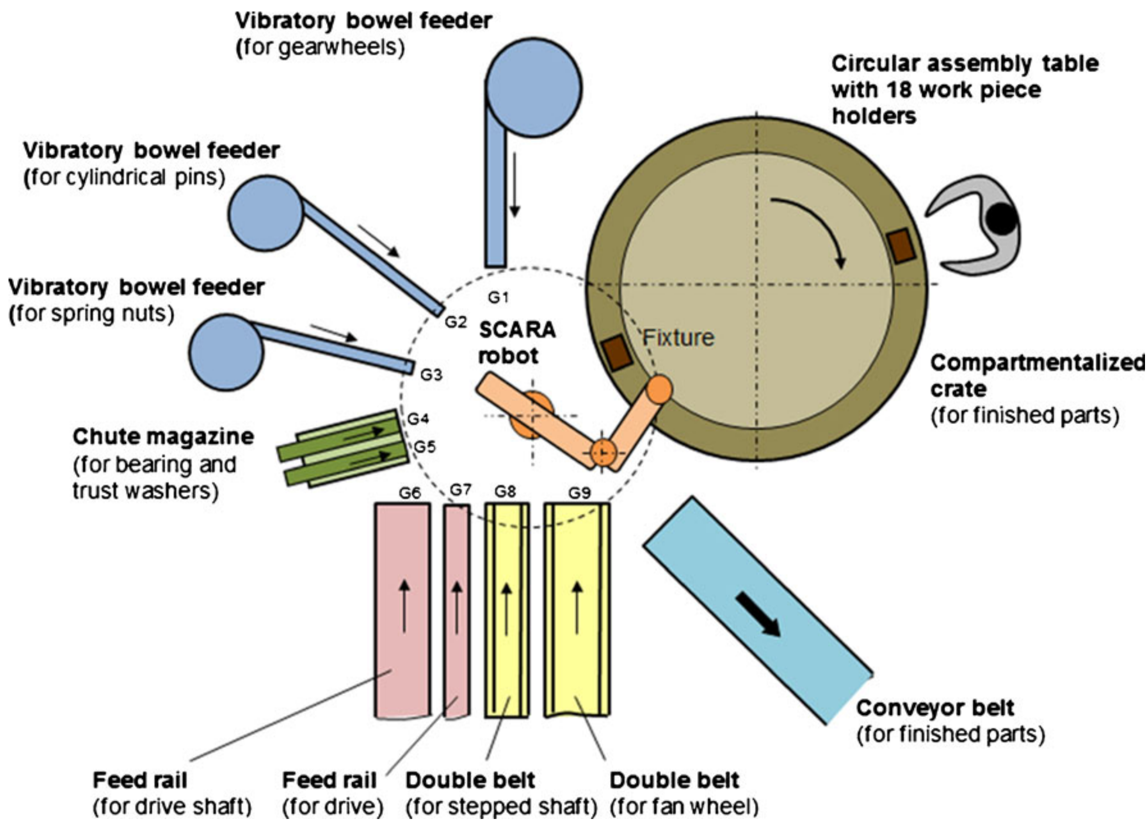
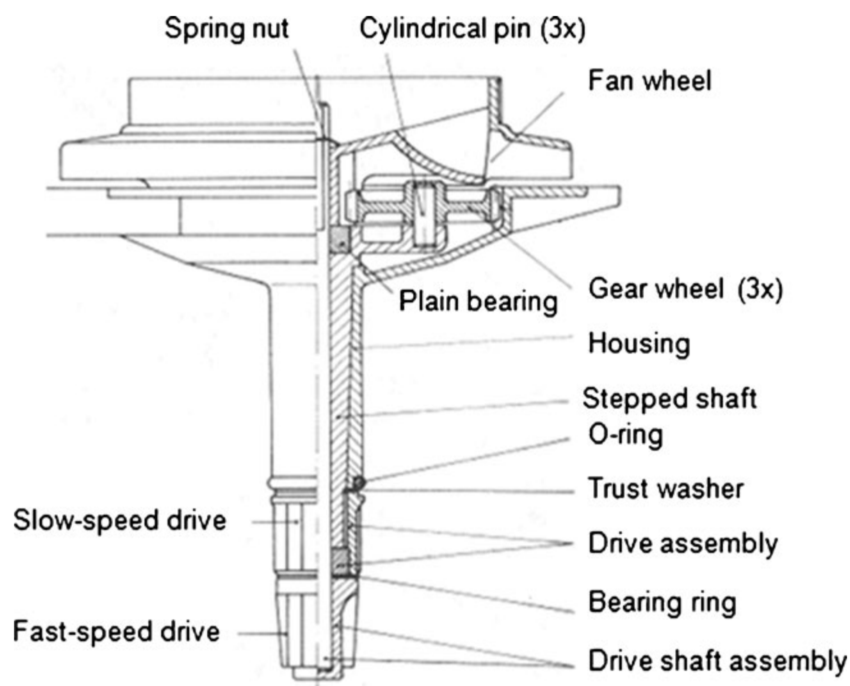


Fig. 4 Domestic appliance drives assembly system (G1…G9 are gripping points) (adapted from [34])

assembly robot. The arrangement makes 18 similar operations possible so that the gripper change times are distributed over 18 similar operations. The operator has the task of removing the housing manually from a compartmentalized crate and placing it in the assembly fixture. The different gripper systems required are placed in the immediate vicinity of the gripping point in order to achieve the shortest possible distances between gripper change actions and

Fig. 5 Domestic appliance drive (adapted from [34])



gripping [34]. A description of the equipment and their assignments is as follows:

- A SCARA robot is placed in the centre of the cell. Robot Gripping points G1 to G9 are positioned within the working area of the robot. The robot is used for both material handling and assembly.
- The gearwheels, cylindrical pins and spring nuts are oriented by three vibratory bowl feeders and fed to the gripping points via discharge rails.
- The bearing ring and thrust washer are picked from chute magazines and then placed by the robot at gripping points G4 and G5.
- The drive shaft, drive, stepped shaft and fan wheel are placed and arranged manually on feed rails or double-belt conveyors and transported to the gripping points G6, G7, G8 and G9, respectively.
- A circular table with 18 work piece holders is positioned upstream of the SCARA robot. This arrangement makes 18 successive similar assembly operations possible to minimize the gripper change time.
- The worker is in charge of placing the housing in the assembly fixture and observing the automatic feeding equipment and assembly operations and, if necessary, fix any faults or malfunction.
- The different grippers required are placed in the immediate vicinity of the gripping points in order to minimize the robot travel distances between positions of gripper change and gripping.

Each piece of equipment in the assembly system is analysed and the classification code is generated for all equipment. The various digit values and description of each field of the system equipment are listed in Tables 6, 7, 8, 9, 10, 11 and 12.

The two feed rails used for feeding the drive and the drive shaft are assumed to have same characteristics; hence, they are having same complexity index. The two double-belt feeders are similar to the two feed rails except that they do not have parts holders (digit#5) and they are having active orientation devices (digit#7). Their complexity index is calculated as I_{MHS}=0.396. The conveyor belt is similar to the feed rails except it has pallets to hold parts (digit#5). Its complexity index is calculated as I_{MHS}=0.365.

Two of the three vibratory bowl feeders are similar (N=3, n=2), the two feed rails are similar (N=2, n=1) and the two double belts are similar (N=2, n=1), plus one conveyor belt (N=1, n=1). Therefore, the total number of the MHS equipment is $N = 3 + 2 + 2 + 1 = 8$. The unique number of the MHS equipment is $n = 2 + 1 + 1 + 1 = 5$.

Equations 4, 6 and 7 are then used to calculate machine, material handling and buffer equipment, respectively. The calculated values of equipment complexity and the number of pieces of equipment are listed in Table 13.

Assuming that all three equipment classes contribute equally to total system complexity (i.e. w_1=w_2=w_3=1), the complexity of the domestic appliance drive assembly cell/system can then be calculated using Eq. 8 as:

$$C_{\text{system}} = 1.536 + 3.255 + 2.069 = 6.860$$

Sometimes different pieces of equipment in a class can end up having the same or a very similar value of complexity index, although they have a different collection of

Table 6 SCARA robot (machine equipment)

#	Machine CC	Description	Digit value	Digit value	Normalized value
1	Structure	Fixed[a]	1	3	0.333
2	*N* axes of motion	*N*	4[b]	6	0.667
3	*N* workheads	*N*	1	2	0.500
4	*N* spindles	*N*	1	2	0.500
5	Tools (Gripper)	Changeable	2	2	1.000
6	Tool magazine	None	1	3	0.333
7	Pin fixtures	Fixed	1	2	0.500
8	Mode	Programmable	2	2	1.000
9	Type	Non-adaptive	1	2	0.500
10	Access	Limited	2	3	0.667
11	Structure	Modular	2	3	0.667
12	Mode	Programmable	2	2	1.000
13	Difficulty	High	3	3	1.000
14	Mode	Fully automated	3	3	1.000
15	Power	Powered	2	2	1.000
16	Fault detection	Auto	2	2	1.000
I_M=0.536					

[a] SCARA robot generally has fixed structure; modular SCARA robots are also available [36]

[b] SCARA robot generally has 4-DOF. However, higher DOF SCARA robots are also available [37]

Table 7 Vibratory bowel feeder (MHS equipment) for cylindrical pins and spring nuts

#	MHS CC	Description	Digit value	Maximum value	Normalized value
1	Type	Feeder	7	7	1.000
2	Structure	Fixed	1	2	0.500
3	Motion	Uni-directional, synchronized	1	4	0.250
4	Path	Fixed	1	2	0.500
5	Parts holder	None	1	4	0.250
6	Part types	Single	1	2	0.500
7	Parts orientation	Passive	1	2	0.500
8	Mode	Programmable	2	2	1.000
9	Type	Non-adaptive	2	2	1.000
10	Access	Limited	2	3	0.667
11	Structure	Fixed	1	3	0.333
12	Mode	Programmable	2	2	1.000
13	Difficulty	Low	1	3	0.333
14	Mode	Semi-automated	2	3	0.667
15	Power	Powered	2	2	1.000
16	Fault detection	Manual	1	2	0.500
I_{MHS}=0.387					

Table 9 Feed rail (MHS equipment) for drive and drive shaft

#	MHS CC	Description	Digit value	Maximum value	Normalized value
1	Type	Monorail	2	7	0.286
2	Structure	Fixed	1	2	0.500
3	Motion	Uni-directional, asynchronized	2	4	0.500
4	Path	Fixed	1	2	0.500
5	Parts holder	Fixture	3	4	0.75
6	Part types	Single	1	2	0.500
7	Parts orientation	Passive	1	2	0.500
8	Mode	Programmable	2	2	1.000
9	Type	Non-adaptive	2	2	1.000
10	Access	Open	1	3	0.333
11	Structure	Modular	2	3	0.667
12	Mode	Programmable	2	2	1.000
13	Difficulty	Medium	2	3	0.667
14	Mode	Semi-automated	2	3	0.667
15	Power	Powered	2	2	1.000
16	Fault detection	Manual	1	2	0.500
I_{MHS}=0.424					

characteristics and they are not interchangeable. In this specific example, equipment of the same type and characteristics, such as the two vibratory feeders, the two feed rails and the two double-belt feeders, have the same complexity index.

Equipment of the same type/class, but with different characteristics, will result in different complexity code digit values, and these pieces of equipment will be considered as a unique variant within the class and hence add to the complexity due to increased variety and information content. This will add to the total number of unique pieces of equipment. For example, if all pieces of equipment in Table 13 were different (even if they were of the same type), this will result in increasing the

Table 8 Vibratory bowel feeder (MHS equipment) for gear wheels

#	MHS CC	Description	Digit value	Maximum value	Normalized value
1	Type	Feeder	7	7	1.000
2	Structure	Fixed	1	2	0.500
3	Motion	Uni-directional, synchronized	1	4	0.250
4	Path	Fixed	1	2	0.500
5	Parts holder	None	1	4	0.250
6	Part types	Single	1	2	0.500
7	Parts orientation	Active	2	2	1.000
8	Mode	Programmable	2	2	1.000
9	Type	Non-adaptive	2	2	1.000
10	Access	Limited	2	3	0.667
11	Structure	Fixed	1	3	0.333
12	Mode	Programmable	2	2	1.000
13	Difficulty	Low	1	3	0.333
14	Mode	Semi-automated	2	3	0.667
15	Power	Powered	2	2	1.000
16	Fault detection	Manual	1	2	0.500
I_{MHS}=0.434					

Table 10 Conveyor belt (MHS equipment)

#	MHS CC	Description	Digit value	Maximum value	Normalized value
1	Type	Conveyor	1	7	0.143
2	Structure	Fixed	1	2	0.5
3	Motion	Uni-directional, asynchronized	2	4	0.5
4	Path	Variable	1	2	0.5
5	Parts holder	Pallets	2	4	0.5
6	Part types	Single	1	2	0.5
7	Parts orientation		1	2	0.5
8	Mode	Programmable	2	2	1
9	Type	Non-adaptive	2	2	1
10	Access	Open	1	3	0.333
11	Structure	Modular	2	3	0.667
12	Mode	Programmable	2	2	1
13	Difficulty	Low	1	3	0.333
14	Mode	Semi-automated	2	3	0.667
15	Power	Powered	2	2	1
16	Fault detection	Manual	1	2	0.5
I_{MHS}=0.365					

Table 11 Chute magazine (buffer analysis)

#	Buffer CC	Description	Digit value	Maximum value	Normalized value
1	Type	Magazine	1	4	0.250
2	Part types	Single	1	2	0.500
3	Access	FIFO	1	3	0.333
4	Location	Separate	2	3	0.667
5	Mode	Manual	1	2	0.500
6	Type	Non-adaptive	1	2	0.500
7	Access	Open	1	3	0.333
8	Structure	Fixed	1	3	0.333
9	Mode	Manual	1	2	0.500
10	Difficulty	Low	1	3	0.333
11	Mode	Semi-automated	2	3	0.667
12	Power	Powered	2	2	1.000
13	Fault detection	Manual	1	2	0.500
I_B=0.248					

unique number of equipment to be n=8 and the MHS complexity becomes C_{MHS} 4.443, which is higher than the earlier values of 3.255. The second case study below further illustrates some similar type equipment with different complexity values due to their different characteristics.

5.2 Case study 2: assembly of a three-pin power plug

This case study illustrates not only the use of the proposed complexity metric to measure the assembly system complexity but also using it to compare assembly system alternatives in the context of complexity. Two assembly system configurations that are used for the assembly of a three-pin electric power plug (Fig. 6) are analysed. The first and the second system configurations are shown in Figs. 7 and 8, respectively.

Table 12 Circular table (buffer analysis)

#	Buffer CC	Description	Digit value	Maximum value	Normalized value
1	Type	Indexing tables	2	4	0.500
2	Part types	Multiple	2	2	1
3	Access	FIFO	1	3	0.333
4	Location	Separate	2	3	0.667
5	Mode	Programmable	2	2	1.000
6	Type	Non-adaptive	1	2	0.500
7	Access	Limited	2	3	0.667
8	Structure	Fixed	1	3	0.333
9	Mode	Manual	1	2	0.500
10	Difficulty	Medium	2	3	0.667
11	Mode	Semi-automated	2	3	0.667
12	Power	Powered	2	2	1.000
13	Fault detection	Manual	1	2	0.500
I_B=0.363					

Table 13 Domestic appliance drives assembly system analysis

Class	Equipment	I	$\bar{I}$	n	N	C
Machine	SCARA	0.536	0.802	1	1	1.536
MHS	Vibratory feeder	0.387	0.689	5	8	3.255
	Vibratory feeder	0.387				
	Vibratory feeder	0.434				
	Feed rail	0.424				
	Feed rail	0.424				
	Double belt	0.396				
	Double belt	0.396				
	Conveyor belt	0.365				
Buffer	Chute magazine	0.248	0.581	2	2	2.069
	Circular table	0.363				
System complexity						6.680

The first system consists of the following equipment:

- Two vibratory bowel feeders stacked one on top of the other, making use of a vision-system to feed pin 2 and pin 3
- A linear vibratory feeder for feeding pin 1
- A pallet magazine to feed the fuse clip subassembly and the cover
- A vibratory bowel feeder for feeding the fuse
- An automatic screwdriver positioned under the fixture to assemble screw 5
- An index-transfer system provided with pallets to remove the acceptable assemblies
- A SCARA robot provided with a gripper exchange system with grippers positioned in the work area of the robot
- The worker role in this assembly system includes the feeding and removal of the fixture, material supply (such as filling the parts magazines), removal of assemblies, repairing jams, system setup and adjusting system components as needed. Hence, this is treated as an automatic assembly cell/system

The second system consists of the following equipment and corresponding assembly operations (Fig. 8):

- Three pallet magazines to feed base subassembly and the fuse clip, as well as the cover
- Four circular vibratory feeders to feed pin 1, pin 2, pin 3 and the fuse
- A screwdriver unit to be handled by the robot to assemble screw 5
- Power-and-free transport system for the automatic feeding and removing of fixtures

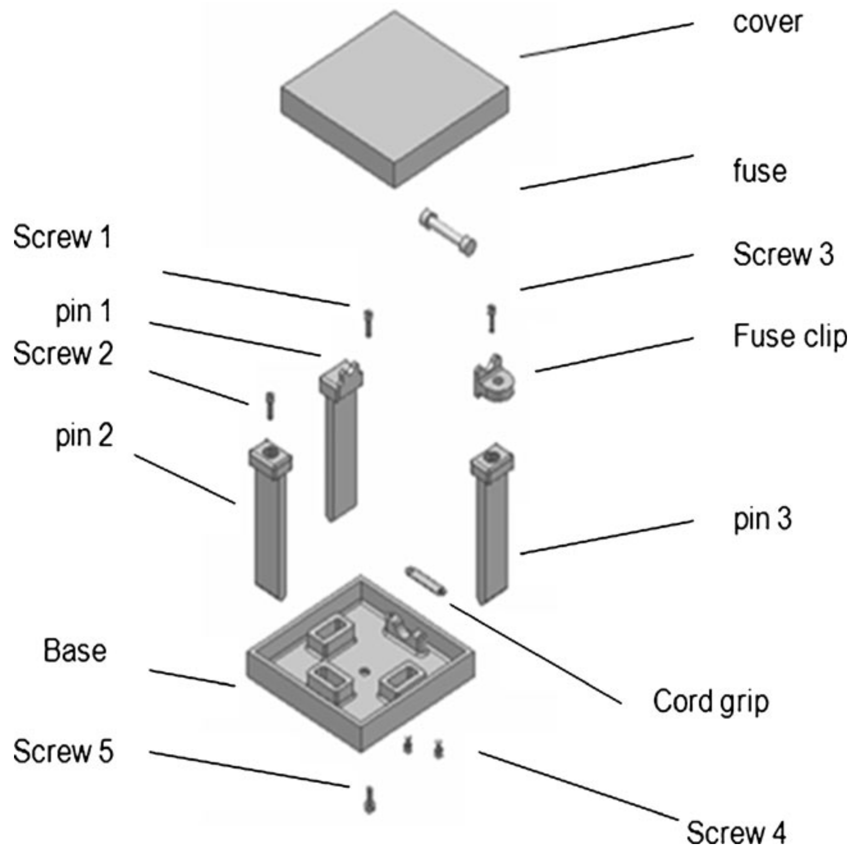


Fig. 6 Three-pin electric power plug (adapted from [35])

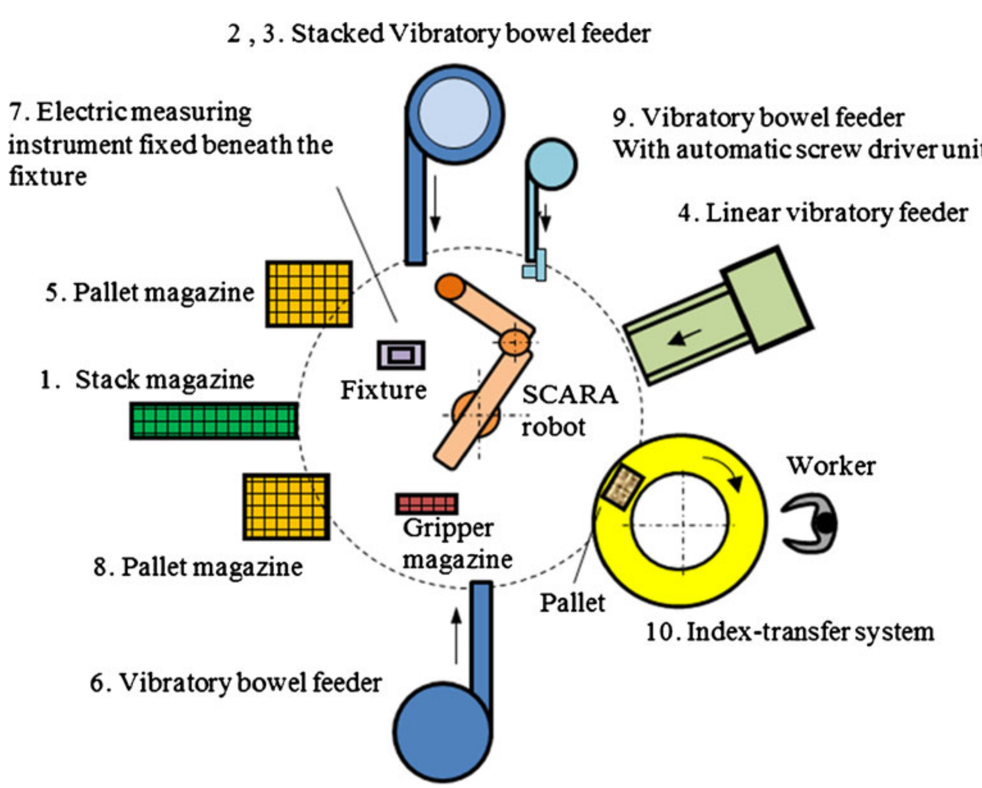


Fig. 7 First system structure (adapted from [35])

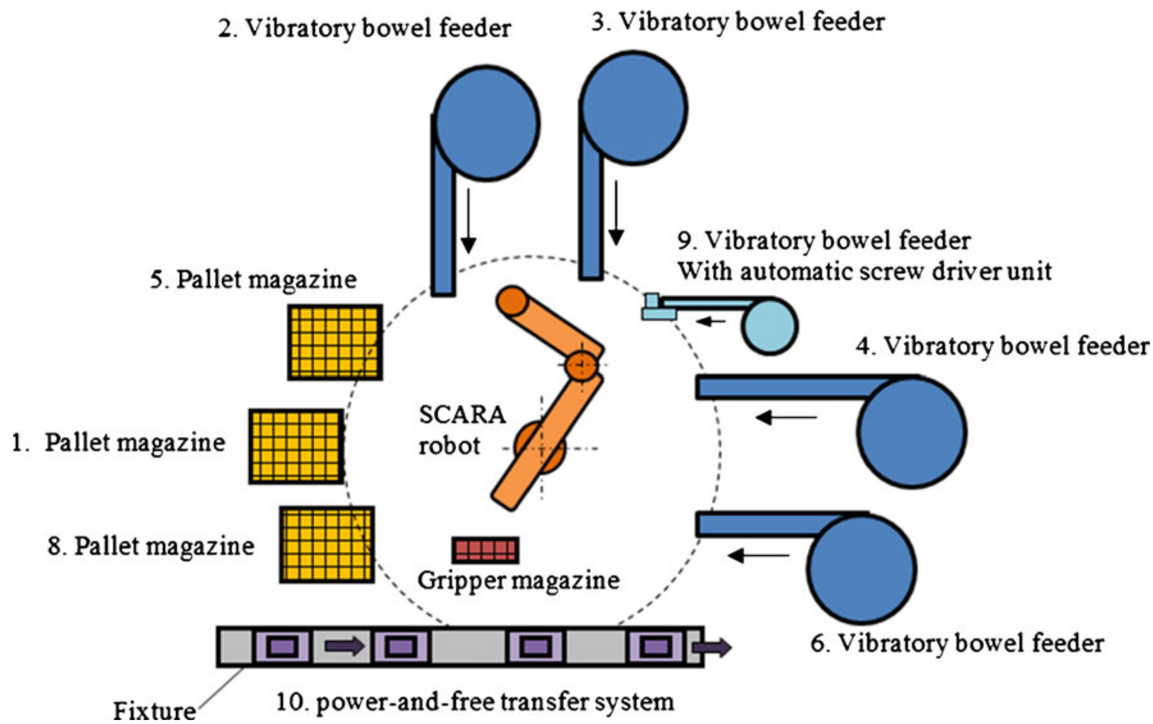


Fig. 8 Second system structure (adapted from [35])

- The operator tasks consist of supplying material, remedying of jams, system setup and if necessary the adjustment of system components
- The remaining system components are consistent with the first system structure described above

The numbers shown in Figs. 7 and 8 correspond to the numbering of the following assembly operations:

1. Feed the subassembly base by a stack magazine (first system) or by a pallet magazine (second system)
2. Feed pin 2 by a vibratory bowel feeder
3. Feed pin 3 by a vibratory bowel feeder
4. Feed pin 1 by a linear vibratory feeder (first system) or by a vibratory bowel feeder (second system)

5 and 8. Feed fuse clip by a pallet magazine

6. Feed cover by a vibratory bowel feeder
7. Check the quality of the assembly by electrical measuring instrument
9. Assemble screw 5 by automatic screw driver unit
10. Removal of acceptable assemblies by index-transfer system (first system) or by power-and-free transfer system (second system)

All system components are analysed and the classification code is generated for each field. The detailed code descriptions of the different pieces of equipment of the two systems are detailed in Tables 23, 24, 25, 26, 27, 28, 29, 30 and 31 of "Appendix 2".

Table 14 compares the equipment and complexity indices for both systems. Complexity indices, number of pieces of equipment including unique ones and complexity measures of all equipment of the two systems are shown in Tables 15 and 16, respectively.

Assuming all three class types (machines, MHS and buffers) contribute equally to the total system complexity (i.e. the weights values are 1), then both system complexities can be calculated using Eq. 8 as:

Table 14 Equipment and complexity indices comparison

Part name	Process #	Equipment of 1st system	Equipment of 2nd system
Base subassembly	1	Stack magazine	Pallet magazine
Pin 2	2	Stacked vibratory bowel feeder	Vibratory bowel feeder
Pin 3	3		Vibratory bowel feeder
Pin1	4	Linear vibratory feeder	Vibratory bowel feeder
Fuse subassembly	5	Pallet magazine	
Fuse	6	Vibratory bowel feeder	
–	7	Electric measuring instrument	
Cover	8	Pallet magazine	
Screw	9	Automatic screw driver	
Finished product	10	Index-transfer table	Power-and-free transfer conveyor
–	–	SCARA robot	SCARA robot

Table 15 Complexity indices, number and complexity measures of the first system

Class	Equipment	I	$\bar{I}$	n	N	C
Machine	SCARA robot	0.460	0.460	1	1	1.460
MHS	Stacked vibratory feeder	0.438	0.348	3	4	2.549
	Vibratory bowel feeder	0.318				
	Vibratory bowel feeder	0.318				
	Linear vibratory feeder	0.318				
Buffer	Stack magazine	0.247	0.258	3	4	2.340
	Pallet magazine	0.182				
	Pallet magazine	0.182				
	Indexing table	0.421				

First system:

$$C_{\mathrm{system1}} = 1.460 + 2.549 + 2.340 = 6.349$$

Second system:

$$C_{\mathrm{system2}} = 1.460 + 2.378 + 1.030 = 4.868$$

The second system complexity is 4.868 compared to 6.349 for the first system. Assembly machines are the same for both systems, which gives the same values of machine complexity “C_{M}”. Although the second system has a higher number of material handling equipment “N_{MHS}”, they have less diversity “$n_{\mathrm{MHS}}/N_{\mathrm{MHS}}$” and, hence, less complexity index “I_{MHS}”, which results in less material handling equipment complexity “C_{MHS}”. Similarly, buffer equipment analysis of the second system shows lower complexity index “I_{B}”, lower diversity “$n_{\mathrm{B}}/N_{\mathrm{B}}$” and a lower number of equipment “N_{B}” than the first system. This results is less buffer complexity “C_{B}”.

Table 16 Complexity indices, number and complexity measures of the second system

Class	Equipment	I	$\bar{I}$	n	N	C
Machine	SCARA robot	0.460	0.460	1	1	1.460
MHS	Vibratory bowl feeder	0.434	0.347	3	6	2.378
	Vibrator bowl feeder	0.434				
	Vibratory bowl feeder	0.434				
	Vibratory bowl feeder	0.434				
	Vibratory bowl feeder with screw driver unit	0.531				
	Power-and-free transfer	0.458				
Buffer	Pallet magazine	0.182	0.182	1	3	1.030
	Pallet magazine	0.182				
	pallet magazine	0.182				

6 Summary and conclusions

In designing any assembly system, a number of trade-offs are made considering function, cost as well as complexity, which is known to affect performance, quality and reliability. Complexity is an important characteristic that merits exploring and modelling at the early design stages. The economic importance of assembly in the chain of product manufacturing steps has led to extensive efforts to improve the efficiency and cost-effectiveness of assembly operations. One way of achieving this is by measuring and managing the complexity of assembly systems.

A structural classification coding scheme has been used to measure the assembly system complexity. The code characterizes the complexity of the various equipment within the assembly system, such as machines, material handling equipment and buffers equipment. The control, programming and operation of this equipment are considered as common. In addition to the information content captured by the generated complexity indices, the number of equipment and their diversity were also incorporated to measure the total static/structural complexity of automated assembly systems built in by virtue of its design and characteristics.

The developed SCC structural classification code helped in measuring the structural complexity of the various pieces of equipment found in assembly systems as well as the whole system complexity. Integrating and aggregating individual complexities into an overall system complexity makes it easier to compare system design alternatives.

The model is based on the structural characteristics of the assembly equipment. Hence, the model is applicable to automatic and the equipment in hybrid assembly systems but not the manual assembly operations or systems.

The proposed model was demonstrated by measuring the structural complexity of a domestic appliance drives assembly system. Two alternate assembly systems used for the assembling a three-pin electric power plug were analysed and compared based on their complexity. The complexity metric was able to identify the complexity of each class of equipment within the system and the total assembly system complexity as well. In the second system, 6.71% less material handling equipment complexity and 55.98% less buffer equipment complexity and reducing diversity resulted in a reduction of the total assembly system complexity by 23.33%.

The developed models can be used as decision support tools to identify and manage sources of complexity, rationalize the assembly systems design alternatives and select the least complex one that meets the functional requirements. This will ultimately reduce assembly cost and time, improve productivity and quality and increase profitability and competitiveness.

Appendix 1: Equipment characteristics and codes

This appendix presents the annotations of the various digits of the SCC as shown in Tables 17, 18, 19, 20, 21 and 22.

Table 17 Machine type CC annotations

Digit number	Description	Explanation
1	Fixed structure	Machine components cannot be changed or replaced
	Modular structure	Structure modular design allows the possibility of replacing some modules of the machine
	Changeable structure	Both hard (add or remove some components of the machine structure) and soft (operation and control software) are changeable
2	*N* axes of motion	Axes of motion are all axes which are controlled and moved during the assembly process
		N is the total number of axes of motion—it ranges from 1 to 6
3	*N* workheads	A workhead performs the actual attachment of the component. Typical workheads include automatic screwdrivers, staking or riveting machines, welding heads and other joining devices
		N is the total number of workheads. A robot has 1 workhead; other assembly machines could have more than 1 workhead
4	*N* spindles	Spindles are very specific to some machines; it rotates about a rotary axis and is independent from it in direction of the rotary axis (translation)
		N is the total number of spindles. A robot is considered to have 1 spindle; other machines could have more than 1 spindle
5	Fixed tools	Tools cannot be adjusted, changed or removed
	Changeable tools	Tools can be modified, changed or adjusted
6	No Tool magazine	Tool magazine is an arrangement of multiple tools that allows a machine to rapidly change from 1 operation to the next
		Some machines have no tool magazine
	Fixed tool magazine	The magazine cannot be replaced or removed
	Replaceable tool magazine	The magazine cannot be replaced or removed
7	Fixed pin fixtures	A fixture that securely holds a part for a certain operation
		The fixed fixture is part specific and cannot be changed or expanded
	Moving pin fixtures	Moving fixtures is the opposite of fixed fixtures

Table 18 Handling equipment CC annotations

Digit number	Description	Explanation
1	Conveyor	A conveyor is a horizontal, inclined or vertical device for moving or transporting bulk material, packages or objects in a path pre-determined by the design of the device and having points of loading and unloading
		Many kinds of conveyors are available such as conveyor belts, chain conveyor and roller conveyor
	Monorail	A monorail is a single run of overhead track on which carriers (trolleys) travel
	Forklift trucks	A forklift truck is a material handling vehicle designed to move loads by means of steel fingers or forks inserted under a load. Also known as a lift truck
	AGV	An AGV consists of 1 or more computer controlled, wheel-based load carriers that run on the plant floor without the need for a driver. AGVs have defined paths or areas within which they can navigate
	Cranes and gantries	A crane is handling equipment used for lifting and lowering a load and moving it horizontally
		A gantry crane is similar to an overhead crane except that the bridge for carrying the trolley is floor supported rather than overhead supported (wall-mounted)
	Robot	An industrial robot is used in positioning to provide variable programmed motions of loads. Industrial robots also used for parts fabrication, inspection and assembly tasks
		An industrial robot consists of a chain of several rigid links connected in series by revolute or prismatic joints with 1 end of the chain attached to a supporting base and the other end free and equipped with an end effector. The robot's end effector can be equipped with mechanical grippers, vacuum grippers, welding heads, paint spray heads or any other tooling
	Feeder	A common feeder is the vibratory feeder. It is a device that uses vibration to feed small parts to a machine. Vibratory feeders use both vibration and gravity to move material. Gravity is used to determine the direction, either down or down and to a side, and then vibration is used to move the parts
		A common vibratory feeder is bowl shaped
2	Fixed structure	The structure of the MHS equipment cannot be changed
	Reconfigurable structure	The structure can be expanded (shortened) by adding (removing) components
3	Uni-directional motion	Operating or moving or allowing movement in 1 direction only

Table 18 (continued)

Digit number	Description	Explanation
	Bi- directional motion	Operating or moving or allowing movement in 2 usually opposite directions
	Synchronized motion	Make motion exactly simultaneous with the action
	Asynchronized motion	Is the opposite of synchronized motion
4	Fixed path	Some equipment has defined paths which they can navigate. Fixed path guidance refers to a physical guide path (e.g. wire, tape, paint, rail) on the floor that is used for guidance
	Variable path	Variable or free-ranging guidance has no physical guide path (e.g. optical-guided laser-guided)
5	Parts holders	A device used to hold and secure parts. It could be a pallet, a fixture or a gripper
6	Part types	A single or multiple types of parts can be handled by the equipment
7	Parts orientation	Passive orientation, e.g. gravity feeders, and active orientation feeders such as bowel feeders with specific orientation devices

AGV automatic-guided vehicle system

Table 19 Buffers equipment CC annotations

Digit number	Description	Explanation
1	Indexing tables	Mechanical device by which the assembly part is transferred from work point to work point in the sequence of assembly operations
	Magazine	With this type of equipment, parts are stacked into a container that constraints the parts in the desired orientation. Magazines can be subdivided into flat and chute magazines
	Carousel	Equipment used to store items for eventual picking or retrieval. There are 2 types of carousels horizontal and vertical carousel
	ASRS	AS/RS refers to a variety of means under computer control for automatically depositing and retrieving loads from defined storage locations
2	Part types	A single or multiple types of parts can be stored or retrieved
3	FIFO access	The way of organizing and manipulation of parts is first in, first out
	LIFO access	The way of organizing and manipulation of parts is first out, first in
	Random access	No specific order of organizing and manipulation of parts
4	Location	A buffer could be integrated with machine, or next to machine, or could be a central buffer that serves more than 1 machine

AS/RS automatic storage and retrieval system

Table 20 Controls CC annotations

Digit number	Description	Explanation
1	Mode	Assembly equipment can be controlled manually or automatically
2	None-adaptive control	Also known as open loop control. It does not use feedback to determine if its output has achieved the desired goal of the input
	Adaptive control	Also known as closed loop control. It feeds the output of the system back to the inputs of the controller
3	Access	The way that user interacts with controller. 3 types exist: open, limited, closed access
4	Fixed structure	No change is allowed in the control software
	Modular structure	Limited hooks are provided for replacing some modules of the controller
	Reconfigurable structure	Total plug and play type of control system that allows adding or removing some components of the controller

Table 21 Programming CC annotations

Digit number	Description	Explanation
1	Mode	An assembly equipment can be manual or programmable
2	Difficulty	The effort and time of programming by user. It ranges from low to high difficulty

Table 22 Operation CC annotations

Digit number	Description	Explanation
1	Mode	Is the level of automation of the operation. It can be manual, semi-automated or fully automated operations
2	Power	Some equipment require power to operate; some are operated manually
3	Fault detection	Faults and errors can be detected manually by operator, or automatically by sensors

Appendix 2: Equipment characteristics and codes

This appendix presents the structural classification code analysis of the three-pin electric power plug assembly systems. Tables 23, 24, 25, 26, 27, 28, 29, 30 and 31 show the main characteristics, normalized digit value and complexity index of individual equipment of the assembly system.

Table 23 SCARA robot (machine analysis)

#	Machine CC	Description	Digit value	Max value	Normalized value	I_M
1	Structure	Fixed	1	3	0.333	0.460
2	*N* axes of motion	*N*	4	6	0.667	
3	*N* workheads	*N*	1	2	0.500	
4	*N* spindles	*N*	1	2	0.500	
5	Tools	Changeable	2	2	1.000	
6	Tool magazine	None	1	3	0.333	
7	Pin fixtures	Fixed	1	2	0.500	
8	Mode	Programmable	2	2	1.000	
9	Type	Non-adaptive	1	2	0.500	
10	Access	Limited	2	3	0.667	
11	Structure	Fixed	1	3	0.333	
12	Mode	Programmable	2	2	1.000	
13	Difficulty	Medium	2	3	0.667	
14	Mode	Fully automated	3	3	1.000	
15	Power	Powered	2	2	1.000	
16	Fault detection	Auto	2	2	1.000	

Table 24 Index transfer (buffer analysis)

#	Buffer CC	Description	Digit value	Max value	Normalized value	I_B
1	Type	Indexing tables	2	4	0.500	0.421
2	Part types	Single	1	2	0.500	
3	Access	FIFO	1	3	0.333	
4	Location	Separate	2	3	0.667	
5	Mode	Programmable	2	2	1.000	
6	Type	Non-adaptive	1	2	0.500	
7	Access	Limited	2	3	0.667	
8	Structure	Fixed	1	3	0.333	
9	Mode	Manual	1	2	0.500	
10	Difficulty	Medium	2	3	0.667	
11	Mode	Semi-automated	2	3	0.667	
12	Power	Powered	2	2	1.000	
13	Fault detection	Automatic	2	2	1.000	

Table 25 Magazine (buffer analysis)

#	Buffer CC	Description	Digit value	Max value	Normalized value	I_B
1	Type	Magazine	1	4	0.250	0.182
2	Part types	Single	1	2	0.500	
3	Access	FIFO	1	3	0.333	
4	Location	Separate	2	3	0.667	
5	Mode	Manual	1	2	0.500	
6	Type	Non-adaptive	1	2	0.500	
7	Access	Open	1	3	0.333	
8	Structure	Fixed	1	3	0.333	
9	Mode	Manual	1	2	0.500	
10	Difficulty	Low	1	3	0.333	
11	Mode	Manual	1	3	0.333	
12	Power	Un-powered	1	2	0.500	
13	Fault detection	Manual	1	2	0.500	

Table 26 Bowel feeder (MHS analysis)

#	MHS CC	Description	Digit value	Max value	Normalized value	I_{MHS}
1	Type	Feeder	7	7	1	0.318
2	Structure	Fixed	1	2	0.5	
3	Motion	Uni-directional, synchronized	1	4	0.25	
4	Path	Fixed	1	2	0.5	
5	Parts holder	None	1	4	0.25	
6	Part types	Single	1	2	0.5	
7	Parts orientation	Passive	1	2	0.5	
8	Mode	Programmable	2	2	1.000	
9	Type	Non-adaptive	1	2	0.500	
10	Access	Open	1	3	0.333	
11	Structure	Fixed	1	3	0.333	
12	Mode	Programmable	2	2	1.000	
13	Difficulty	Low	1	3	0.333	
14	Mode	Semi-automated	2	2	0.667	
15	Power	Powered	2	2	1.000	
16	Fault detection	Manual	1	2	0.500	

Table 27 Stacked bowl feeder (MHS analysis)

#	MHS CC	Description	Digit value	Max value	Normalized value	I_{MHS}
1	Type	Feeder	7	7	1	0.438
2	Structure	Fixed	1	2	0.5	
3	Motion	Uni-directional, synchronized	1	4	0.25	
4	Path	Fixed	1	2	0.5	
5	Parts holder	None	1	4	0.25	
6	Part types	Multiple	2	2	1	
7	Parts orientation	Active	2	2	1	
8	Mode	Programmable	2	2	1.000	
9	Type	Non-adaptive	1	2	0.500	
10	Access	Open	1	3	0.333	
11	Structure	Fixed	1	3	0.333	
12	Mode	Programmable	2	2	1.000	
13	Difficulty	Medium	2	3	0.667	
14	Mode	Semi-automated	2	2	0.667	
15	Power	Powered	2	2	1.000	
16	Fault detection	Automatic	2	2	1.000	

Table 28 Vibratory bowl feeder with screw driver (MHS analysis)

#	MHS CC	Description	Digit value	Max value	Normalized value	I_{MHS}
1	Type	Feeder	7	7	1	0.408
2	Structure	Fixed	1	2	0.5	
3	Motion	Uni-directional, synchronized	1	4	0.25	
4	Path	Fixed	1	2	0.5	
5	Parts holder	None	1	4	0.25	
6	Part types	Single	1	2	0.5	
7	Parts orientation	Passive	1	2	0.500	
8	Mode	Programmable	2	2	1.000	
9	Type	Adaptive	1	2	0.500	
10	Access	Limited	1	3	0.333	
11	Structure	Modular	2	3	0.667	
12	Mode	Programmable	2	2	1.000	
13	Difficulty	Low	1	3	0.333	
14	Mode	Semi-automated	2	2	0.667	
15	Power	Powered	2	2	1.000	
16	Fault detection	Automatic	2	2	1.000	

Table 29 Linear vibratory feeder (MHS analysis)

#	MHS CC	Description	Digit value	Max value	Normalized value	I_{MHS}
1	Type	Feeder	7	7	1	0.318
2	Structure	Reconfigurable	2	2	1	
3	Motion	Uni-directional, synchronized	1	4	0.25	
4	Path	Fixed	1	2	0.5	
5	Parts holder	None	1	4	0.25	
6	Part types	Single	1	2	0.5	
7	Parts orientation	Passive	1	2	0.5	
8	Mode	Programmable	2	2	1.000	
9	Type	Non-adaptive	1	2	0.500	
10	Access	Limited	1	3	0.333	
11	Structure	Fixed	1	3	0.333	
12	Mode	Programmable	2	2	1.000	
13	Difficulty	Low	1	3	0.333	
14	Mode	Semi-automated	2	2	0.667	
15	Power	Powered	2	2	1.000	
16	Fault detection	Manual	1	2	0.500	

Table 30 Stacked magazine (buffer analysis)

#	Buffer CC	Description	Digit value	Max value	Normalized value	I_B
1	Type	Magazine	1	4	0.250	0.247
2	Part types	Multiple	2	2	1.000	
3	Access	LIFO	2	3	0.667	
4	Location	Separate	2	3	0.667	
5	Mode	Manual	1	2	0.500	
6	Type	Non-adaptive	1	2	0.500	
7	Access	Open	1	3	0.333	
8	Structure	Fixed	1	3	0.333	
9	Mode	Manual	1	2	0.500	
10	Difficulty	Low	1	3	0.333	
11	Mode	Manual	1	3	0.333	
12	Power	Un-powered	1	2	0.500	
13	Fault detection	Manual	1	2	0.500	

Table 31 Power-and-free conveyor (MHS analysis)

#	MHS CC	Description	Digit value	Max value	Normalized value	I_{MHS}
1	Type	Conveyor	1	7	0.143	0.403
2	Structure	Fixed	1	2	0.500	
3	Motion	Uni-directional, asynchronized	2	4	0.500	
4	Path	Variable	2	2	1.000	
5	Parts holder	Pallet	2	4	0.500	
6	Part types	Single	1	2	0.500	
7	Parts orientation	Passive	1	2	0.500	
8	Mode	Programmable	2	2	1.000	
9	Type	Non-adaptive	1	2	0.500	
10	Access	Limited	2	3	0.667	
11	Structure	Modular	2	3	0.667	
12	Mode	Programmable	2	2	1.000	
13	Difficulty	Medium	2	3	0.667	
14	Mode	Automated	2	2	0.833	
15	Power	Powered	2	2	0.667	
16	Fault detection	Manual	1	2	0.500	

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