Convertibility Measures for Manufacturing Systems

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Abstract
With increased consumer demands for a wider variety of products in changeable, unpredicted quantities, manufacturing system responsiveness has become increasingly important for industry competitiveness. Manufacturers need systems that can be rapidly adjusted with regard to both functionality and throughput capacity over the lifetime of the system. Convertibility is defined as the capability of a system to adjust production functionality, or change from one product to another. End-users of manufacturing systems are struggling with the issue of how to measure and quantify convertibility. Metrics for convertibility are proposed in this paper so that different manufacturing systems can be compared with respect to this area of performance. These metrics are based on assessments of the configuration itself, and the system components such as machines and material handling devices. Metrics for quantifying convertibility are useful for comparing system configurations during the early phases of design, without requiring detailed product or process plan information.

Keywords:
Manufacturing system, Performance analysis, Convertibility

1 INTRODUCTION

Consumers of manufactured goods today desire a greater variety of products in unpredictable quantities. Traditional dedicated manufacturing lines (DML) were not designed to handle these types of demands. Although flexible manufacturing systems (FMS) can handle product variety [1], they can be justified only for very small volumes. Researchers are investigating more cost-effective technological solutions that will allow manufacturers to be more responsive to the market, such as reconfigurable manufacturing systems [2]. These systems are appropriate for both medium and high volume industries, particularly when frequent product changes are expected.

In large manufacturing systems the production is done in stages, where product is partially processed in one stage and then transferred to the next. These manufacturing systems may have different configurations, defined by the way that the machines are arranged in the stages and the way that they are connected. It has been shown that the configuration of a system can have significant effects on performance [3], [4]. Performance can be assessed in many areas including quality, productivity, and responsiveness. Responsiveness includes both convertibility and capacity scalability. Convertibility is defined as the capability of a system to rapidly adjust production functionality, or change from one product to another. Better responsiveness usually makes a system more expensive. The manufacturing industry has been struggling with issues related to quantifying system responsiveness. A key research question asks what features enable certain systems to be rapidly adjustable and how can those features be measured so that designers can compare multiple system alternatives and justify the higher cost of more convertible systems. Responsiveness issues and various performance metrics including flexibility and reconfigurability were introduced in [5], [6], [7], [8], and [9], but more well-defined metrics for responsiveness are needed, particularly in the area of convertibility.

During the early phases of manufacturing system design, convertibility metrics can be defined using the intrinsic characteristics of the components and configuration that make one system inherently more convertible than another. This approach is useful when detailed information about products and process plans is not yet available. In addition, there are situations where convertibility assessments of manufacturing systems are desired without consideration of the products that they will manufacture, such as when capital investment decisions regarding equipment purchases must be justified. Accordingly, in this paper such metrics for convertibility are proposed.

2 SYSTEM CONVERTIBILITY

System convertibility includes contributions due to machines, their arrangements or configuration, and material handling devices. These factors are combined in Equation (1) for an overall intrinsic assessment of system convertibility.

$$C_S = w_1 C_C + w_2 C_M + w_3 C_H \tag{1}$$

where C_C, C_M, and C_H, are convertibility metrics associated with the configuration, machine, and material handling, respectively, which are further defined in subsequent sections such that each metric has a scale of 1-10. The weights, w_1, w_2, and w_3 can be adjusted. Manufacturers have the option of selecting different types of systems such as dedicated, flexible, or reconfigurable, as well as the level of convertibility. The configuration, machine, and material handling components that comprise these systems provide varying levels of convertibility to the system which greatly affects adaptability for future alternate uses of the same system, such as when product mix or product designs change over time.

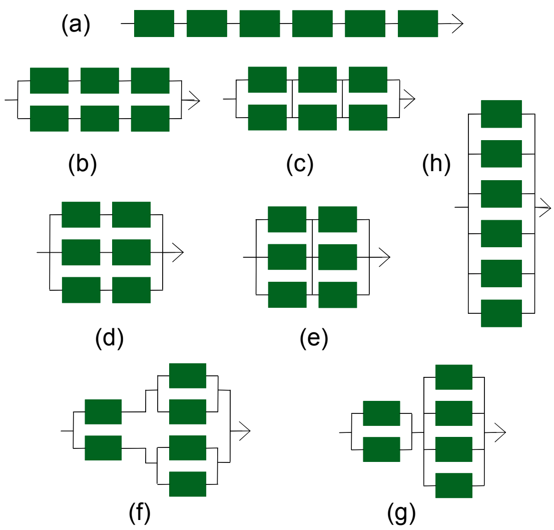

Figure 1: Sample Configurations of Six Machines.

3 CONFIGURATION CONVERTIBILITY

Configuration refers to the arrangement and connections of machines in a manufacturing system, examples of which are shown in Figure 1. Pure serial configurations such as the six-stage line in (a) have only one part flowpath through the system. Pure parallel configurations such as (h) have as many flowpaths through the system as there are machines. In other words, each machine can process the workpiece from start to finish. Hybrid configurations are combinations of serial and parallel instances. Of particular interest is a comparison between (b) and (c) or a comparison of (d) and (e). These pairs of configurations have the same arrangement of machines, but different material handling connections. Asymmetric configurations have flowpaths with different numbers of machines, and thus, different process plans. These configurations are not considered here due to less frequent industry use. Configuration convertibility, C_C, is dependent upon the minimum increment of conversion, the routing connections, and the number of replicated machines.

3.1 Increment of Conversion

The minimum increment of conversion (*I*) was briefly introduced in [7], where it was one of many factors used to select preferred manufacturing system configurations. It is an important indication of how quickly new or different products can be introduced. For example, configuration (a) in Figure 1 has a minimum increment of conversion of 1.00, or 100%, that is, in order to introduce a new product, the entire line must be shut down, changed over, and restarted. Configuration (b), however, can be partially converted to a new product after only 50% of the machines have been shut down and reconfigured. This is valuable when a company wants to introduce a new product to the market as quickly as possible, and then later ramp up to full production.

3.2 Routing Connections

In a manufacturing system, a greater number of routing connections indicates a higher degree of convertibility. The number of routing connections in each configuration (*R*) is counted by including connections between machines as well as connections to an input and output station. For example, configuration (a) in Figure 1 has seven routing connections whereas configuration (b) has eight. Configuration (c) has twelve routing connections due to the fact that crossover is allowed between processing stages. For configurations of n machines, the maximum number of connections is given in Equation (2).

$$R_{\max} = 2n + f\sum_{i=1}^{n-1} i \tag{2}$$

If connections between machines allow only unidirectional flow *f*=1, but for bidirectional flow *f*=2. For any configuration of 6 machines with only unidirectional connections, such as those in Figure 1, R_{max} equals 27.

3.3 Replicated Machines

Certain configurations allow for easier scheduling of the production of more than one product at a time. This is important when a company expects part mix demands to vary over time. The minimum number of replicated machines at a particular stage in the process plan (*X*) dictates the number of part types that can be produced without requiring changeovers. This number is similar to configuration width, as defined in [10].

For example, a serial manufacturing line, or transfer line, such as configuration (a) in Figure 1 typically has only one flowpath by which parts progress through the system. At each stage of the process plan, there is only one machine present. Thus, if more than one part is to be produced, the line must be stopped, purged of old products, converted, and ramped up again, all of which consumes valuable production time. By contrast, a flexible manufacturing system with six CNC machines in parallel, each capable of completely manufacturing a part, could produce up to six different part types, as configuration (b). Configurations (f) and (g) however, could only simultaneously produce two products efficiently since the first processing stage has just two replicated machines, not four. If more than two products are produced on the system simultaneously, the system productivity is substantially reduced. Being able to produce more than one part type at a time is also valuable when manufacturers want to produce prototypes of future products while current products are still being manufactured at a reduced rate.

3.4 Measure of Configuration Convertibility

The three factors discussed above, minimum increment of conversion, routing connections, and number of replicated machines are used in Equation (3) to provide a preliminary assessment of configuration convertibility.

$$C_C' = \left(\frac{R * X}{I}\right) \tag{3}$$

where *I*, *R*, and *X* were defined above. Equation (4) below is used to normalize C_C' relative to a serial system with the same number of machines, and to adjust the scale so that all systems being compared fall within a range of one to ten.

$$C_C = 1 + \frac{Log\left(\dfrac{C_C'}{C_{C,serial}'}\right)}{Log\left(\dfrac{C_{C,K-Parallel}'}{C_{C,K-serial}'}\right) * \dfrac{1}{9}} \tag{4}$$

If *K* is the maximum number of machines in any system that is being considered, then the pure parallel configuration of *K* machines is defined to have a C_C value of 10. All serial configurations have a C_C value of 1. This logarithmic transformation converts C_C to a 1-10 scale. Configuration convertibility can then be combined with machine and material handling convertibility metrics to find system convertibility, as in Equation (1).

	I	R	X	C_C	Rank
a	1.00	7	1	1.00	8
b	0.50	8	2	4.32	7
c	0.50	12	2	5.20	6
d	0.33	9	3	6.35	4
e	0.33	15	3	7.46	2
f	0.33	10	2	5.69	5
g	0.33	14	2	6.43	3
h	0.17	12	6	10.00	1

Table 1: Configuration Convertibility for Sample Configurations Shown in Figure 1.

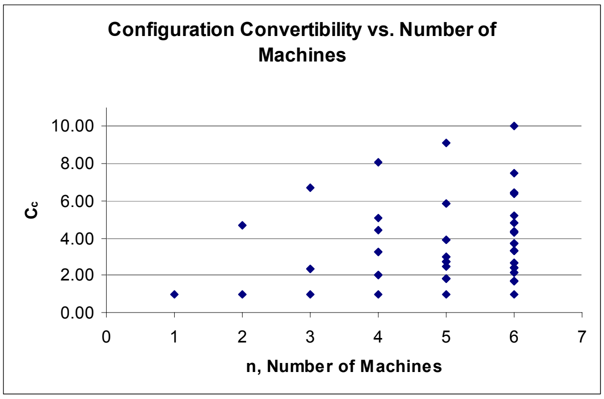

Figure 2: Configuration Convertibility for Symmetric Configurations of up to Six Machines.

The configuration convertibility metric was used to compare the sample configurations from Figure 1, and the results are given in Table 1. Configuration convertibility was also assessed for symmetric configurations of up to six machines, shown in Figure 2.

4 MACHINE CONVERTIBILITY

System convertibility is dependent not only on the configuration that is selected, but also on machine convertibility, C_M, which is found using Equation (5).

$$C_M = \frac{\sum_{i=1}^{N} C'_M}{N} \tag{5}$$

The machine convertibility for each of the N individual machines in the system, C'_M, is based on the premise that some machines have features and characteristics that make them inherently more convertible. These features include whether the machine is:

Q1. equipped with an automatic tool changer or multi-head spindle;

Q2. easily reprogrammed, with flexible software;

Q3. modular, with flexible hardware components;

Q4. equipped with flexible fixturing capability;

Q5. equipped with a large capacity tool magazine.

As shown in Figure 3, these questions help determine a rough estimate of machine convertibility, C'_M.

5 MATERIAL HANDLING CONVERTIBILITY

One important factor in system performance that has not yet been included in flexibility or convertibility metrics is

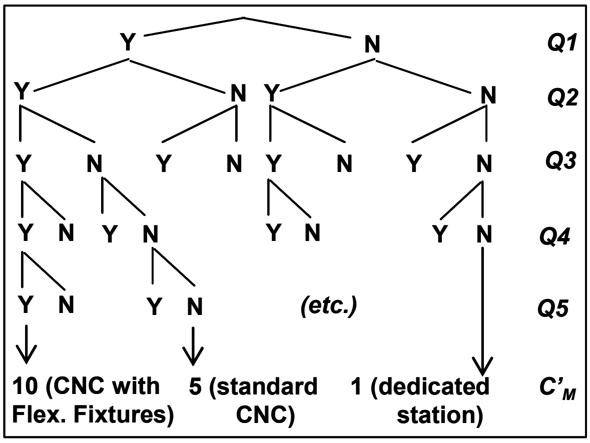

Figure 3: Machine Convertibility, C'_M

the nature of the material handling devices that are used. This metric, C_H, in Equation (6) is developed in a manner analogous to the machine convertibility.

$$C_H = \frac{\sum_{i=1}^{M} C'_H}{M} \tag{6}$$

The C'_H metric for each material handling device that connects machines is found by assessing if it is:

Q1. following a free route or not;

Q2. multidirectional;

Q3. reprogrammable;

Q4. asynchronous motion;

Q5. automatic.

It must be noted that the most flexible or convertible solutions may also incur larger investment costs. For material handling, having people carry workpieces from station to station is very flexible. For example, an Intel plant that produces 50 products simultaneously has people carry wafer cartridges between stations. This solution, however, may be very expensive and is not always the best utilization of human resources.

6 APPLICATIONS

An industry case which was studied earlier with regard to productivity is now used to compare the convertibility of two different configurations shown in Figure 4 [3]. Both configurations (a) and (b) have 18 CNC machines with relatively small tool magazines and manual material handling. Thus, C_M, C_H, and C_C are found and then C_S is calculated using equal weighting factors, as shown in Table 2, cases (a) and (b).

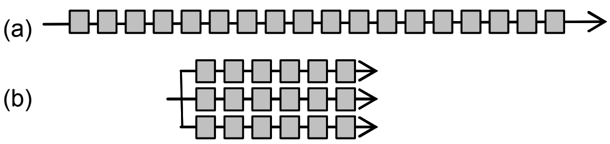

Figure 4: Industry Case Configurations.

	N	C_M	C_H	X	I	R	C_C	C_S
a	18	5	9	1	1	19	1	5
b	18	6	9	3	.33	21	4.22	6.4

Table 2: Convertibility Calculations for Industry Cases.

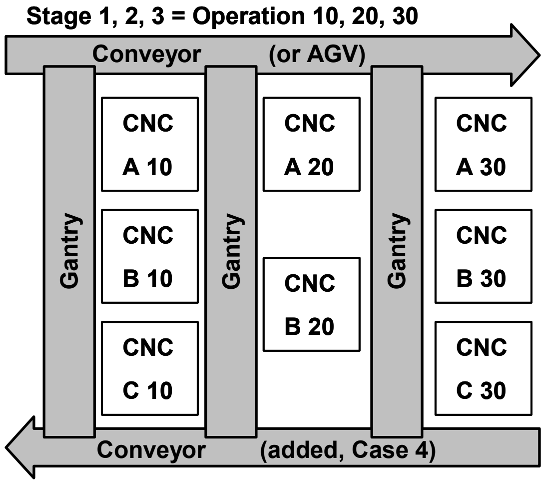

Figure 5: Future Industry Configuration for a Reconfigurable Manufacturing System.

	N	C_M	C_H	X	I	R	C_C	C_S
1	8	5	3.5	2	.375	51	5.92	4.81
2	8	6	3.5	2	.375	51	5.92	5.14
3	8	5	5.5	2	.375	51	5.92	5.47
4	8	5	3.75	2	.375	72	6.42	5.06
5	8	6	3.75	2	.375	72	6.42	5.39

Table 3: Convertibility Calculations for Industry Cases.

A second example studied here is a planned industry application of a reconfigurable manufacturing system shown in Figure 5. Many variations of this system can be compared, as reported in Table 3 and described below:

Case 1 – eight CNC machines (C'_M=5), material handling by three gantries (C'_H=4) linked with a single belt conveyor that allows forward motion only (C'_H=2)

Case 2 – extra large tool magazines

Case 3 – AGV (C'_H=10) instead of forward conveyor

Case 4 – a reverse conveyor (C'_H=3)

Case 5 – incorporates cases 2 and 4 with large capacity tool magazines and bidirectional conveyor capability.

Thus, the system in case 5 shows a 12% improvement in system convertibility over the baseline system in case 1 (from 4.81 to 5.39).

7 CONCLUSIONS

When companies design and install new systems, they must be concerned not only with the products being manufactured today, but also those that will be made throughout the lifetime of the system. Thus, the ability to respond to future market conditions is important. By measuring the convertibility of the configuration, machines, and material handling elements, the convertibility metrics defined here provide a quantitative assessment for characteristics of manufacturing systems that make certain design alternatives inherently better than others in terms of responsiveness.

Intrinsic metrics of convertibility are particularly useful during the early phases of design, when detailed product and process plan information may not be known. These assessment techniques can be used to compare candidate systems and configurations. It is often the case that more flexible and convertible systems require a higher initial investment. Intrinsic convertibility metrics can be used to justify the purchase of these systems, particularly for manufacturers who deal in highly volatile markets or have products that require frequent design changes.

Another method for assessing convertibility could expand on the intrinsic measures presented here to include product information. When detailed information is known about the products that are being manufactured and their respective process plans, product-based metrics can be used to assess convertibility requirements. These metrics can include the time required to make conversions or the cost of a changeover. A further situation which has not yet been accounted for is the case where a system has many flexible machines mixed with a few dedicated stations that happen to fit the process plan for that family of products.

8 ACKNOWLEDGMENTS

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