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State space representation of routing flexibility

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Abstract

This paper describes a state space representation for sequencing and routing flexibility in manufacturing systems. Routing flexibility is represented using five different stages as follows: (i) Precedence Graph of Operations; (ii) State Transition Graph of Manufacturing Operation Sequences; (iii) State Transition Graph of Manufacturing Operation Routes; (iv) Disjunctive Normal Form (DNF) Representation of Manufacturing Sequences; and (v) DNF Representation of Manufacturing Routes. Each representation is able to represent sequencing and routing flexibility at different levels of detail. The third representation is capable of enumerating all possible manufacturing operation routes that can be applied to a certain part, being the most complete representation. Bounds for computation of some of the representations are presented to help users select the most suitable for a specific problem context. The efficacy of the representation is demonstrated through its application to problems such as job route selection and routing flexibility measure.

Keywords: Flexible manufacturing systems; Routing flexibility; Sequencing flexibility; State space representation

1. Introduction

Flexibility has become one of the key concepts in contemporary manufacturing—an important attribute of manufacturing systems that enables companies to become competitive in a very dynamic environment. In particular, flexibility is the *piéce de rèsistence* of flexible manufacturing systems (FMSs) (Kochikar & Narendran, 1992). It is this important attribute that distinguishes FMS from the traditional high-volume, process-dedicated production systems like the automated transfer line. Flexibility is defined by some authors as 'the ability of the manufacturing system to cope with the changes effectively' (Gupta & Buzacott, 1989). Due to the great number of different kinds of environmental changes (machine breakdowns, volume changes, introduction of new products), it is very difficult to find a single index characterizing the flexibility of automation (Azzone & Bertelé, 1991). Consequently, it is necessary to divide the concept of flexibility into elementary concepts that are related to certain kinds of disturbances and elements of a manufacturing system.

Four flexible conditions are associated with the manufacturing of a part, namely sequencing flexibility, machine flexibility, routing flexibility, and processing flexibility (Benjaafar & Ramakrishnan, 1996; Hutchinson & Pflughoeft, 1994; Sethi & Sethi, 1990). Sequencing flexibility refers to the possibility of altering the sequence of manufacturing operations for a given part, taking into account the restrictions of the design specification. Machine flexibility relates to the possibility of an operation being performed in more than one machine. Routing flexibility refers to the ability of

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a manufacturing system to permit sequencing and machine flexibility simultaneously. Process flexibility provides alternative paths for completing a manufacturing process, which includes different manufacturing or process sequences. Several researchers have demonstrated the potential for improving system performance using routing flexibility (Benjaafar, 1994; Hancock, 1989). Since flexibility can be an important attribute of a manufacturing system in terms of improving its performance, the development of models and algorithms that are able to represent sequencing and routing flexibility is an important step towards an effective design, operation and control of flexible manufacturing systems. Moreover, as the introduction of flexibility in manufacturing systems requires high investments, such a development is also an important step towards a better understanding of the consequences of having these kinds of flexibility. The representation will help manufacturing engineers to introduce sequencing and routing flexibility with a minimal loss of efficiency.

The choice of the route in which parts are manufactured can affect the efficiency of the manufacturing process. For example, one route may require less fixturing, and less changing of tools. The choice of manufacturing routes is made by human experts. The availability of a systematic procedure able to generate all feasible manufacturing routes that is proven correct and complete will guarantee that all and only feasible manufacturing routes will be generated. Thus, choosing representations for routing flexibility is an important decision both in creating an efficient manufacturing route planner and in designing control system for the manufacturing process.

Several methodologies for representing sequencing and routing flexibility have been utilized. Lin and Solberg (1991) have presented an AND/OR digraph formalism to represent sequencing flexibility. The operations are represented by the nodes of the graph and the precedence constraints are represented by the arcs of the graph. An OR node means that only one of its children must be performed; whereas an AND node means that all the children must be performed. Wei and Egbelu (2000) used the same approach to represent process alternatives from product geometric design data, focusing on alternative tool approach direction. Unfortunately, this kind of representation may produce process plans for which no machine exists in the system (Benjaafar, 1994).

Benjaafar and Ramakrishnan (1996), Borenstein (2000), and Yang, Qiao, and Jiang (1998) have proposed representations based on OR digraphs (or trees), where the operations are represented by nodes and arcs to represent the precedence constraints. Kochikar and Narendran (1992) have used a state transition formalism supported by Petri nets to represent all possible states of a certain part. However, both representations are impractical due to the considerable computing resources required to store them. They grow rapidly as the complexity of a process plan increases, as a consequence of the multiple representation of the same operation for different sequences.

Benjaafar (1994) has introduced a set theoretic model that simultaneously captures three flexible conditions associated with part manufacturing, namely sequencing, routing, and processing flexibility. This model, however, does not explicitly represent feasible manufacturing operation sequences. Feasible process plans should be obtained by recurrently applying functions to feasible sequences, starting with the initial operation. Thus, Benjaafar's model is a framework in which all representation could be based on rather than an implementable method.

Despite the diversity of representations, there is a gap in the literature of a representation that simultaneously comprises the following aspects:

- ability to derive all feasible manufacturing operation sequences from a description of the manufacturing plan of a part;
- development of a correct and complete algorithm to generate with efficiency the designed representation.
- a compact representation of all possible manufacturing operation sequences.

The main objective of this work is to develop such a representation simultaneously incorporating these aspects. This paper presents a compact representation for the set of all possible manufacturing operation sequences and routes for a given part using a state space representation. State space analysis is one of the most suitable techniques to analyze manufacturing systems as discrete dynamic systems (Kochikar & Narendran, 1992). In this approach, a system is represented by states corresponding to possible situations that can exist in it. The idea behind such representation is to select a minimum set of elemental attributes (called state variables) to prune the complete state to a smaller, but representative space state. The main objective is to obtain reduced-dimension models that approximate the original system behavior (Hwang, Guo, & Shieh, 1991). The routing flexibility uses five different representation stages, able to represent routing flexibility at different levels of detail. Bounds for the computation of the five stages are presented to facilitate the user in selecting the best one for a specific problem.