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Research Article

Configuration Optimization Method of Reconfigurable Manufacturing Systems

Xie Xiaowen, Zheng Beirong and Xue Wei
College of Mechanical and Electrical Engineering, Wenzhou
University, Wenzhou Zhejiang 325000, China

Abstract: In the study, the dynamic variability of reconfigurable manufacturing systems has been addressed and the optimization scheme of component reconfiguration has been also presented. According to the product line process changes, the production line configuration for different products has been identified; stage as a unit, the system reconfiguration path model based graph theory is built up; the weight of each edge is defined according to economic, time and process constraints and the genetic algorithm is adopted to optimize and obtain the optimal/suboptimal reconfiguration path from one configuration to another configuration of multi-stage production line. At last, an actual example, a manufacturing line composed of three RMTs, is also presented. The results show that the methodology can concurrently optimize the process plans and configurations with high computation efficiency.

Keywords: Genetic algorithm, multi-stage production line, optimization method, reconfiguration

INTRODUCTION

Modern manufacturing enterprises are facing unpredictable, rapidly changing and growing global competition and other issues. Reconfigurable Manufacturing Systems (RMS) have some unique characteristics, changeable structures, modular and fast reconfiguration ability and it can adapt to different aspects of changes, new product to market/product parts/customer needs, technologies and policies and regulations and other ones, which is driven by fierce global competition, improved customer quality and innovative technologies and reflects the balance among economy, technology and society (Koren *et al*., 1999; Xie and Li, 2006; Hu *et al*., 2008).

Son *et al*. (2010) presented a design method for economical reconfigurable manufacturing equipments. To address configuration path changes caused by production need changes, the genetic algorithm and configuration similar index had been adopted that had reduced cost of each needing stage. Tang *et al*. (2004) represented manufacturing resource reconfiguration actions as nodes of active networks and then the shortest path search algorithm in graph theory had been adopted to search the optimal path to get the best reconfiguration schemes. But the authors considered only the behaviors of serial reconfigurations. Lou *et al*. (2006) used the Dijkstra algorithm to obtain the shortest path to eventually get the best system reconfiguration schemes. However, it did not consider self reconfigurations of manufacturing resources and also could not guarantee the lost of the optimal reconfiguration path. Shabaka and Elmaraghy (2007) used kinematic chain to represent behavior relations of manufacturing resources and mutual constraints of multiple components and according to new configuration requirements, the optimal reconfiguration paths of various components of resources could be given.

The above researches considered the dynamic optimization problems of manufacturing system production resource reconfiguration, however, there are following issues:

- Most works were based on deterministic need scenes and not considered state changes driven by random events, also impact of various random factors on self reconfiguration paths.
- Involved reconfiguration ways were too simple and only considered the way of serial reconfiguration, without asynchronous, concurrent situations and competitive and conflict relations.

CONFIGURATION MODEL OF RMS

According to structural characters of parts, the n-bit features $\{F_1, F_2,\dots, F_n\}$ are decomposed and the implementation of each character F_i needs a series of m operations $\{OP_1, OP_2,\dots, OP_m\}$. Each OP can be processed in different ways. For example, the complement of half precision production of hole can adopt the mode: bore, expand or hinge. The OPs can be concentrated to several stages $\{ST_1, ST_2,\dots, ST_l\}$, which named multi-stage production line. Each stage correspond the specific configuration of machine tools.

Corresponding Author: Xie Xiaowen, College of Mechanical and Electrical Engineering, Wenzhou University, Wenzhou Zhejiang, 325000, China

The changes of production parts result in the corresponding adjustment of production line configurations. Adjustment from the original configuration to the new one is named as a reconfiguration process R. R is the composition of a series of reconfiguration actions which can reconfigure the production line from an original configuration to another one? The changing process not only includes reconfiguration actions in the system level, but also those in the device level. Moreover those activities can be serial or concurrent.

Description of reconfiguration path optimization: Reconfiguration path optimization is to design the optimal series of reconfiguration actions according to the initial and destination configurations, given optimization objective.

Definition 1: Reconfiguration path optimization problem is represented as a Four-tuple RP = (G, S, R, ST_i), G is the optimization objective, S is the configuration, R is a series of reconfiguration actions, ST_i is various stage in the production line:

- **G-optimization objective:** The optimization process has multiple optimization objective, G = {(g_1, g_2,…, g_n), w}, g_n represents a component of the target vector, w is the weight of each vector.
- **S-production line configuration:** The production line configuration:

  $$S = (r\,(ST_i^I, ST_j^o), ST_1, ST_2,\ldots, ST_n, n)$$

  where,
  $r\,(ST_i^I, ST_j^o)$ = The input-output relation between each stage
  $r\,(ST_i^I, ST_j^o)$ = 1, the input buffer of i^{th} stage and output buffer of j^{th} stage are connected, otherwise not connected
  n = The number of all stages of production line
  S_i = The initial configuration
  S_d = The destination configuration

- **R-a series of reconfiguration actions:** Through a series of reconfiguration actions, the production line changes from the original configuration to the destination one. Reconfiguration actions are a series of actions to machining equipment and production materials. The production line is composed of various stages. The reconfiguration of production line consists of the reconfiguration of each stage that is the objective configuration is decomposed into multiple stages. Each stage of the initial configuration is in turn mapped to the corresponding stage of the destination configuration. The mapping process is through a series of reconfiguration actions. The reconfiguration actions are limited by the input-output relation between stages. Meanwhile, different reconfiguration actions may bring the changes of cost and production:

  $$O = \{o_1, o_2, \cdots, o_n\}$$

  where, each reconfiguration action O_i can be defined as follows:

  $$o_i = (num_i, str_i, upd_i, c_i, t_i)$$

  where,
  mum_i= The change of the number of each stage
  Str_i = The inner change of each stage such as from serial to concurrent
  upd_i = The configuration change of each stage inner devices, such as changes of inner components, update of control software
  c_i = The cost of the reconfiguration action
  t_i = The time change of the reconfiguration action

- **ST_i-the stage of production line:** A production line is divided into various stages according to achieved processes, for example $ST_i \in ST$, i = 1, 2, .., m.

The configuration change of multi-stage production line in some production cycle is called as a reconfiguration cycle. The reconfiguration action will lead to reconfiguration cost, reconfiguration time and the reconfiguration action processes. To implement the objective, firstly the relation between each reconfiguration action, reconfiguration cost and time are defined, secondly according to stages of production line, the feasible configuration graph is obtained and the weight sum of cost and time is computed, thirdly the definition the weight of each edge is added according to the weight of each edge search the optimal path between two nodes. Furthermore, the solution process is divided into two parts, one is the modeling part based on graph theory and another is the solution by GA, which is shown in Fig. 1.

Formal modeling of manufacturing system path optimization based on the graph theory: Path optimization model of production line during one configuration cycle can be viewed as the shortest path problem, shown in Fig. 2. The production line is divided into various stages, the reconfiguration cost, time and other elements of each stage

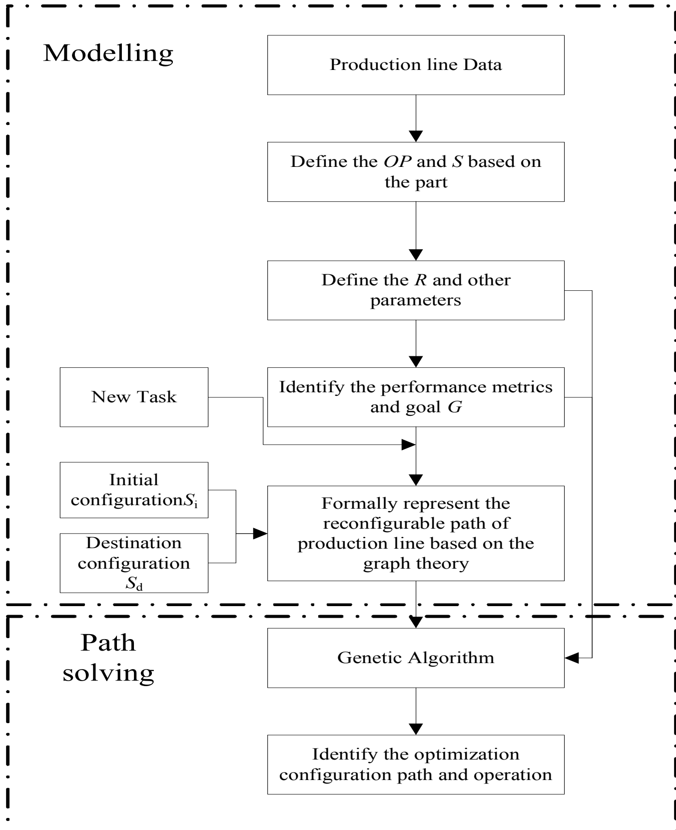

Fig. 1: The path optimization strategy of production line reconfiguration

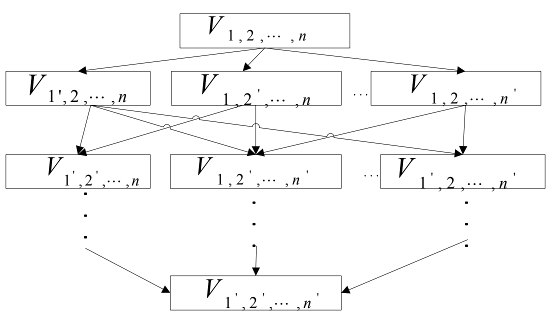

Fig. 2: The reconfigurable path of production line

correspond to the edges between nodes in graph. After various reconfiguration operations, the system reconfigure from the initial configuration to the destination one. For the division of stages is based on the production process of parts, the production line after reconfiguration can guarantee the new production requirements.

Its description is as follows: given a weight directed graph N_D = (V, A, W), V are the vertices, A is the finite edge between nodes, W and is the weight of directed edge.

Assume P is a path from the initial vertex V_s to the final vertex V_t, which caused by R. The weight of path P is the sum of weight of all edges, that is w (P) = $\sum_{i,j \in P} w_{ij}$. The shortest path problem is to solve one path with minimal weight from all paths of the initial vertex V_s to the final vertex V_t, that is $P_{min} = \min \sum_{i,j \in P} w_{ij}$., which is related to G.

During one configuration cycle, the configuration of production line is as the vertex of directed graph. According to the changes of stages by process changes of parts, the reconfiguration actions of each stage can be mapped to the edges of directed graph. The reconfiguration cost, time are calculated to construct the directed graph of production line configuration changes. Therefore, the solution of production line configuration optimal path can be transferred into the shortest path of directed graph.

Genetic algorithm for path solving: In the shortest path problem, GA can quickly get the shortest/sub-optimal path without too many constraints and restrictions.

The adjacent matrix represents whether or not vertex V_i, V_j has shared edges.

Definition 2: Adjacent matrix: For an adjacent matrix of graph with V vertex and e edges, A = [α_{ij}] is an v×v order matrix, where, α_{ij} = 1 represents V_i, V_j are adjacent, α_{ij} = 0 is they are not adjacent or i = j.

- **Chromosome:** For a given graph model, the graph vertex are naturally ordered and then according to this order each candidate vertex is selected as a chromosomal gene. When the gene value is 1 indicates that the corresponding vertex has been selected into this path, otherwise means not. The gene sequence of this chromosome is the appearance sequence of vertices in this path and the length of the chromosome is the number of vertices in the graph.
- **Fitness function:** For a graph with n vertexes, the length of each edge between vertex V_i, V_j is known as P (V_i, V_j) and the length of a path $v_{i1}, v_{i2},\ldots, v_{in}$ from v_{i1} to v_{i1} is defined as the fitness function:

$$f(i) = \sum_{r=1}^{n-1} p(v_{ir}, v_{ir+1})$$

- **Selection operations:** Individuals are selected with a probability proportional to their relative fitness. Namely, the survival probability of short path individual is higher than long path. This ensures that the expected number of offspring of a parent is approximately proportional to its relative performance in the population.
- **Crossover and mutation operations:** The crossover operation is adopted in the selected parent chromosomes and using random generation of random numbers to determine the crossover point, then, in this position on the single-point crossover. Mutation is a chromosomal inversion in a certain gene, that is, from 1 to a 0, or vice versa. The map reflected, for a path to remove or add last vertex.
- **Optimization objectives:** The best/shortest path is to find the smallest weights of selected edges. The definition of the optimization objectives is:

$$G(n) = g_1(n) + g_2(n)$$

where,

g_1 (n) = Reconfigurable cost
g_2 (n) = Reconfigurable time

$$g_1(n) = \alpha_1 \sum g_{ra} + \alpha_2 \sum g_{rd} + \alpha_3 \sum g_{rc}$$

where,

g_1 (n) = The reconfigurable operation cost from vertex V_i to V_{i+1}
g_{ra} = The increasing cost of added equipment during reconfigurable operation
g_{rd} = The decreasing cost of deleted equipment during reconfigurable operation
g_{rc} = The moving cost of moved equipment during reconfigurable operation

Table 1: The coefficients of cost

Coefficients	Value
α_1	1/3
α_2	1/3
α_3	1/3
g_{ra}	2000
g_{rd}	1000
g_{rc}	2500

Table 2: The coefficients of time

Machine tool type M_t	Coefficients value t (j)	Operation type	t_i
Dedicated machine tool	1/5	Add	1.2
Machine centers	1	Remove	0.8
Inspection equipment	1/3	Adjust	1.5

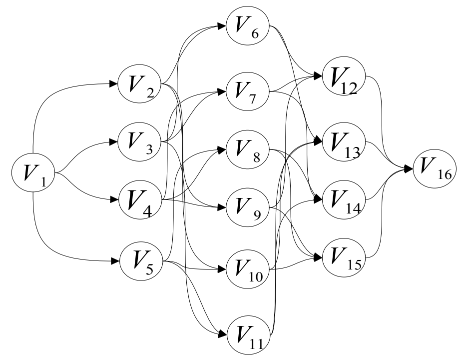

Fig. 3: The directed graph of production line configuration adjustment

$$g_2(n) == \sum_{i=n}^{1} \left(\sum_{j=m} t(j) \times M_t \right)$$

where,

g_2 (n) = The sum of all reconfigurable operation time of a given path from vertex V_1 to V_n
M_t = t Types equipment in the production line
t (i) = The reconfigurable time coefficients of the different machine tools

CASE STUDY

There are 2 types' cylinder parts in production line. The process plan of Part A is milling the surfaces (OP10) →rough process of holes (OP20) →finished process of holes (OP30) →Inspection and leakage (OP40) →fine boring (OP50). The process plan of Part B is milling the surfaces (OP10) →rough, semi-fine process of holes (OP20) →Fine process of slant-holes and holes (OP30) →Inspection and leakage (OP40) →Fine hinge (OP50).

When the product changed from type A to type B, the production line need to be reconfigurable operated. This production line includes five stages and each stage adjusts according to new configuration, such as add/remove machine tools. The reconfigurable paths of production line are showed in Fig. 3.

The Table 1 and 2 are provided by Company. The weight of each edge can be calculated according to the equations of Section "Configuration model of RMS".

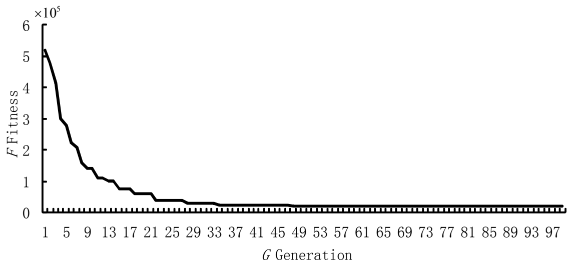

Fig. 4: Optimization curve

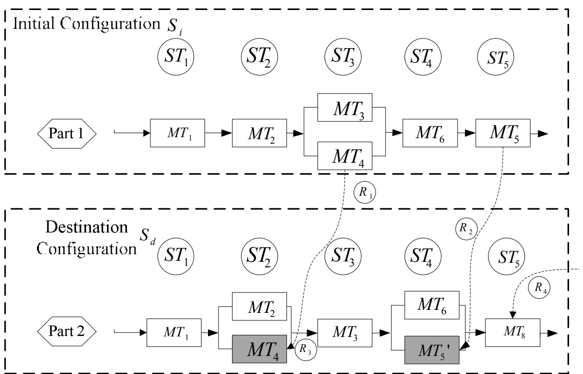

Fig. 5: Reconfiguring the multi-stage production line in the example

The GA, presented in subsection "Genetic algorithm for path solving" is used to solve the directed graph showed in Fig. 2. Then, the optimization curve of best path is showed as Fig. 4.

The best individual of path is $V_1 \Rightarrow V_3 \Rightarrow V_7 \Rightarrow V_{12} \Rightarrow V_{16}$.

Figure 5 shows how the multi-stage production line is reconfigured according to the best individual reconfigurable actions. The machine MT4 is moved from stage 3. MT5 is adjusted and moved to stage 4 from stage 5. In addition, the extra MT8 is added to stage 5. All actions are finished step by step.

CONCLUSION

- The characteristics of reconfigurable manufacturing system are analyzed and the reconfiguration processes is modeled formally using graph theory.
- The optimization goals and every GA operations are determined. Moreover, a case is presented to show the feasibility and effectiveness of the methodology which proposed in this study.

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