Selection of optimal capacity for reconfigurable machines during lean manufacturing

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Abstract. Presently manufacturing industries are facing the challenge of increased market volatility and unpredictability. Capacity control is an effective measure to address this problem by utilizing the flexibility in the plant capacity. This research paper proposes a genetic algorithm (GA) based methodology to optimally select levels of capacity for machines which are reconfigurable in nature. The objective function for the optimization problem is minimization of an error with takt time. Takt as a key feature of lean manufacturing is considered in the model to manufacture the products in a fixed rate as decided by their respective demands and available production time. A hypothetical numerical problem is illustrated to describe the selection methodology, GA computation steps and the solution procedure.

1. Introduction and relevant literature

Lean manufacturing can be described as a collection of tools and methodologies that aim for the elimination of all types of waste in the production process on a continuous basis. Hence it is a systematic approach to not only identify but also eliminate wastes and all non-value-added activities through continuous improvement. It is a manufacturing approach under pull based production. Lean tools help to optimize the flow of work and to completely eliminate waste and enhance adaptability through proper operational strategies. It aims to improve productivity by substantially simplifying the operational structure of the firm so as to understand, implement and manage the business environment. Some of the basic steps to achieve lean systems are discussed here.

Design a lean manufacturing system based on demand-based pull production. The benefits of this concept include decreased cycle time, less inventory, increased productivity and increased use of capital equipment. Secondly, continuous improvement means constant endeavour to identify areas for potential improvements is the key for achieving goals of the firm. It is continuous and gradual improvement of products and processes with simultaneous elimination of unwanted activities. Thirdly, measuring the Overall Equipment Efficiency (OEE) is a set of performance metrics which are suited for lean environments. Also price analysis and time study to assess waste and system effectiveness in the operational processes come under lean systems. One of the major characteristics of lean is takt time. It is a time volume relationship calculated as rhythm or beat for each process of a flow line and used to establish resource definition and line balance. Takt time influences the manufacturing system.
design through all the levels of design hierarchy i.e. overall plant layout, machine design specification, work loop design, etc.

Reconfigurable Machine Tools (RMTs) falls under the broad manufacturing system of reconfigurable manufacturing system. RMTs constitute of modular machines that have a changeable structure. It enables the adjustment of its resources like adding a second spindle unit or changing power input unit according to the need. The reconfigurable machine tool holds the features between a dedicated machine which is designed to machine with high efficiency just one-part type and in large volumes along-with a computer controlled machine which has high level of flexibility in producing variant parts. RMTs are suited for a part family, so programmable, multiple tool spindles that drill simultaneously can be used or a special geometry to machine a given part with conversion period between different parts of the same part family thereby giving customized flexibility. The machines can be quickly reconfigured to the new part geometry within the part family within a short conversion period.

The basic objectives of RMT design are (i) Increment of the rate of production for the machine by addition of machine modules (exactly the capacity needed) and (ii) Incorporation of a new functionality in the machine so that it can produce a new member of the part family (exactly the functionality needed).

In this paper, a model of a manufacturing system is proposed which consists of these futuristic RMTs and the lean concept in terms of takt time is also integrated in the system. An optimal selection strategy for the capacity levels of RMTs is developed through GA to minimize the error compared to takt time of products. In the literature survey, some relevant works related to GA based optimization models in lean and reconfigurable manufacturing are presented.

The work of Brown and Sumichrast [1] presents and tests a grouping genetic algorithm (GGA) in the formation of part families based on their processing requirements and the identification of machine groups based on their ability to process a specific part family. In addition to it the solutions obtained by the algorithm have been tested against several other highly complex heuristics where they are seen to yield far superior results.

Landers et al. [2] investigated the impact of production requirements and performance of various designs of the RMT. This article provided a detailed overview of a new paradigm for machine tools; RMTs. They studied the impact of operational and production needs on the design of RMTs. Three examples were provided illustrating several changes in operational requirements and then RMTs were compared with special machine tools, modular machine tools and flexible CNCs. RMT gives a viable solution in the cases where operating requirements change within the limits prescribed over the life of the machine tools. However, RMTs are found to be cost-effective when operational requirements change. In addition, unlike CNCs, which can meet a variety of operational requirements, RMTs are designed for a specific range of operational requirements and therefore have no wasted resources or functionality.

In the work of Zhao and Wu [3], a GA approach to the machine grouping problems with multiple objectives was presented. The multi objectives involved minimizing costs due to inter-cell and intra-cell part movements, minimizing the total within cell load variation and minimizing exceptional elements. The grouping of machine using genetic algorithm in the production of cells with multiple goals and consideration of several routes is performed.

A multi-objective GA approach was suggested [4] to identify optimal machines in a reconfigurable manufacturing environment. Non-dominated sorting GA gave multiple Pareto optimal solutions based on non-dominance principle. Ali and Deif [5] presented a dynamic model to assess the degree of leanness in manufacturing systems. It examined the dynamics associated with the application of takt time. Results proved that adjusting the cycle times to takt time will enhance the overall system performance. Improvements are observed in the overall service level, overall work-in-progress efficiency and equipment effectiveness.

The research work in [6] presents a new capacity control approach taking into account the potential of the reconfigurable machine tools. The simulation results substantiate the often disregarded potential
of reconfigurable machine tools. Reconfiguration of machine tools presents additional degrees of freedom in terms of production planning and control. The findings demonstrated the ability of RMTs.

The work of Haldurai et al. [7] shows how GA is combined with various other methods and techniques to derive optimal solution, reduce the computation time of retrieval system and the applications of genetic algorithms in various fields. In short it explains how GA can be applied to real world problems.

Shneor [8] introduces applications of reconfigurable machine tools approach within the machine-shop level. RMT can be used to respond to changes in the products or parts to be manufactured, changes in the size of the part, changes in the geometric complexity of the parts, increased rate of production changes in the process of machining and changes in the accuracy of machining. Two different machining processes were used by integrating different types of technologies and modules into the same CNC vertical milling machine.

Section 2 of this paper describes the formulation of the problem in terms of various notations to model the lean manufacturing characteristics. The optimization methodology is presented in section 3 along with objective function and various steps of the GA procedure. In section 4, the optimization results for machine capacity selection as obtained from GA and the performance analysis of GA are presented. The last section contains the conclusion and future directions for the present work.

2. Problem Formulations

2.1 Problem Statement

In the present model, a production system has been considered which incorporates lean based flow of products i.e. products manufactured in a one-piece-flow process. It is assumed that the manufacturing system also has several RMTs that can be adjusted in their capacity and functionality according to the changing needs. Now ‘n’ different types of products required by customers in different demand periods poses a challenge to the system. With every product having an associated predetermined requirement of machines, the different RMTs in the production shop floor need to be adjusted for right capacity for fulfilling the demand.

2.2 Problem Stages

2.2.1 Allocation of time period to each product. The customer demand is variable and fluctuating in nature in a real-life situation. Customers have different demand levels for different products indicated by their respective demand periods, i.e. in a given time frame of T these products are demanded in different quantities. Table 1 illustrates a similar problem scenario with hypothetical data.

| Table 1. Products required in different quantity in the same time frame. |
|---------------------------------------------------------------|
| **Product type** | **P₁** | **P₂** | **P₃** | **P₄** |
| Number required   | 40     | 60     | 40     | 70     |
| Total available time (days) | **T** | **T** | **T** | **T** |

This results in an ambiguity regarding time allocation to the production of a given product type.

2.2.2 The optimal configuration of machines. Takt time represents the time required to manufacture one unit of a product. All the n products here have an associated takt time. But the reconfigurable machine tools (operating at different capacity levels) have discrete processing times with respect to their configuration. Table 2 presents the calculation of takt time for one of the products; P₁. The aim here is to reduce the gap between the takt time and the processing time for each operation performed. This gives maximum machine utilization and production in minimum possible time. Selection of suitable capacity levels of individual RMTsin order to have minimum takt error(E) is the objective of the present model.
Table 2. Takt time calculation for \( P_1 \).

| Product | \( P_1 \) |
|---------|-----------|
| No. required | 40 |
| Demand period (days) | 10 |
| Daily working time (hr/day) | 8 |
| Total working time (hr) | 80 |
| Takt time (hr) | \( \frac{80}{40} = 2.0 \) |

2.2.3 *Determination of the correct sequence.* The system incorporates a lean flow of parts where all these parts are made one by one. The products are not made simultaneously on machines and so they must be given a priority, an order according to which production flow is decided.

Finalisation of some basis to determine the correct order in which the \( n \) different products will be produced is to be developed.

2.2.4 *Selection methodology.* In order to overcome the above mentioned problems and to get the optimum machine capacity configuration, a solution methodology is to be developed using takt time and involves a smaller number of machine reconfiguration for the set of parts to be produced.

3. Methodology

3.1 *Meta-heuristics*

It is a predefined procedure designed to optimize the mathematical model of real-life problem using high specification computational approach. The steps of meta-heuristic are predefined and it gives a large set of solutions which is very big to sample completely. It works with some assumptions about the problem being optimized and may not give globally optimal solutions. Some popular meta-heuristics are genetic algorithm, ant-colony optimization, Tabu search algorithm, memetic algorithm, etc. The present manufacturing model has been optimized using the very versatile genetic algorithm. The programming language used for coding is Python© which gives a very user friendly interface to run the individual parts of program separately.

3.2 *Mathematical Model*

In real industries many products are required in the specific demand period and the demand may change across the demand periods. The hypothetical model considers four different types of products in a specific demand period and total six RMTs available to perform the various operations. For manufacturing of products, different combination of machines is required from the available machines. Some of the notations for the model parameters are given here.

- \( D \) Demand period (total days of the week for the specific demand period)
- \( D_{pi} \) Demand of \( i^{th} \) product
- \( M \) Available machines with reconfiguration attachments
- \( M_i \) \( i^{th} \) machine used in operation for part manufacturing
- \( P_i \) \( i^{th} \) part formed with operations on the machines \( M_p, M_q, M_r \) and so on. (\( p, q, r \) are the number of machine operations required in the part formation)
- \( T \) Takt time calculated for the formation of part in demand period
- \( S_i \) Total time taken by the machines to form the \( i^{th} \) part
- \( E \) Takt error (deviation of processing time from theoretical takt time)
3.3 Objective function formulation

The objective function is to calculate the takt error ‘E’ for each possible configuration of RMTs in order to minimize the error and find the optimal configuration.

Minimize \( E = f(x) = \sum (S_i) - \sum (T_i) \)  

Fitness of random GA population can be calculated using this equation. The various steps of GA based solution methodology are given here with suitable illustrations.

**Step 1:** The first step of the algorithm is to generate a random population of chromosomes representing machine configurations. Three different capacity levels for RMTs are assumed as low, medium, high denoted by L, M and H respectively.

Random population = LMLHMM, MMLHMH and so on.

The random populations of sample size twenty are generated using pseudo-random numbers as presented here.

- MLHMLL
- HHHHLH
- MLLMLL
- LMMHMM
- LHHHHH
- HMHHMH
- MLHMLH
- MLLMHH
- HMLLMM
- HLHMHM
- MMHMLM
- HHLMLL
- HMLHMML
- HLHMLM
- MMLLML
- MLLLHM
- HMLLMM
- HLHMHM
- MMHMLM
- HHLMLL
- LMMMLL
- LMHLML
- MMLLML
- MLLLHML

**Step 2:** To calculate the fitness of random population generated in previous step, equation (1) for objective function is used with the predefined data available for each product and manufacturing operation on machines.

Cells: [(6,4,2), (7,5,2), (8,6,4), (7,4,2), (7,5,3), (6,4,1)]

Products: [(0,1,0,1,0,1), (0,1,0,1,1,0), (1,0,0,1,0,1), (0,1,0,1,0,1)]

This product list and cell were initial assumptions for the products to form the hypothetical situation and calculate the fitness. Cell list assumed to give the processing time for the operation in different configurations and next product list assumed to give the information about the machine operation.

**Step 3:** In the demand period more than one product would be formed so the available time for the production of parts should be divided in proper manner/proportion to comply with takt time. So, the time division were done on the basis of percentage proportion of average process time and demand of the particular product. The high demand part should have more proportion of demand period. It should also follow the processing time and operating time for completion of part. The time for processing of part equals overall average operating time for each part and this was multiplied with demand to find out the proportion of total time available for each product as in equation (2). Figure 1 illustration of the program logic snippets as applied on Python®.

\[ S_a = \text{average operating time for each machine} \]
\[ T_d = \text{total working hour available in demand period} \]

**Time available for parts** = \[ \frac{(S_a \times D)}{\sum (S_a \times D)} \] \( \times T_d \)  

(2)
Figure 1. An illustration of the program logic snippets as applied on Python.

**Step 4:** Takt time was calculated as in equation (3) for each part as per the time proportion available for respective part.

\[
T \text{ (Takt time)} = \frac{D_{pi}}{\text{Time available for parts}}
\]  

**Step 5:** Fitness of random populated strings in the initial step were calculated with takt time and operating time to get the best fitness of strings.

```
print(fitness)
fitness of each string[0.25, 0.12, 0.33, 0.33, 0.2, 0.14, 0.12, 0.33, 0.12, 0.14, 0.17, 0.33, 1.0, 0.2, 0.14, 0.5, 0.14, 0.2, 0.17, 0.25]
```

Fitness = reciprocal of minimization function = \( \frac{1}{f(x)} \)

**Step 6:** The fitness is used to select parents for mating pools. Range of probability were divided to select parents having better fitness. A proportionate selection as given in equation (4) is applied to select parents.

\[
\text{Probability of } i^{th} \text{ string} = \frac{\text{Fitness of } i^{th} \text{ string}}{\text{Sum of fitness}}
\]  

Cumulative probability and range of probability was derived for each random string for selection of parent’s chromosomes with random number call which lies mostly in the respect to those strings which have large range of probability. Selected parents list with good fitness values is provided here.

```
HHMMMMM    HHMMMMM    MHLMLL    MHLMLL
HHMMMMM    MHLMLL    MHLMLL    MHLMLL
HHMMMMM    MHLMLL    MHLMLL    MHLMLL
HHMMMMM    MHLMLL    MHLMLL    MHLMLL
HHMMMMM    MHLMLL    MHLMLL    MHLMLL
HHMMMMM    MHLMLL    MHLMLL    MHLMLL
```

**Step 7:** To apply genetic operators like cross-over and mutation, probability for these are to be selected. This selection plays a very important role in the convergence of GA. Based on trial and errors, the chromosome probability of mutation which generally have very low value (0.05) compared to the cross-over probability of 0.8.
Parents selected for cross-over illustration are MMLHML and LHMMHL with cross site at 4th number gene. Both chromosomes are divided into two parts from the cross site. First part of parent 1 is joined with the second part of parent 2 and vice-a-versa to get two cross-over off-springs upon which mutation would be applied.

| Parent 1 | MMLHML | Off-spring 1 | MMLHHL |
|----------|---------|--------------|---------|
| Parent 2 | LHMMHL  | Off-spring 2 | LHMMML  |

*Step 8:* During the mutation two random sites are selected and genes would interchange their position in the same chromosome.

Chromosome selected for mutation example is MMHLHL and two randomly selected genes are 2 and 5. Both the genes exchanged their positions during mutation process and the muted off-spring is obtained as given here.

Before mutation: MMLHLH
Muted off-spring: MHIHML

When all the steps of GA are applied and final set of children as a new generation is formed, it likely to have better and improved average fitness compared to previous generation.

*Step 9:* In the final step of GA, the whole process of forming new generation from initial random population is repeated more than hundreds of cycles called number of generations to reach an optimum solution. Set of off-spring formed after each generation is treated as initial population for the next generation.

*Step 10:* After finding the better configuration of machines as per the takt time which gives the minimum takt error, another step for optimization was to find out the optimum sequence of operation for more than one product, which has optimized by the mathematical function to minimize the number of reconfigurations in machines as small as possible. Since, reconfiguration of machine takes an ample amount of setup time which is non-productive time for machine. So, basic concept of sequencing rule is applied to select the sequence with minimum idle time.

4. **Computational results**

The optimal result obtained from GA gives the best configuration for each RMT which can minimize the takt error for a product type in a particular demand period. The final configuration for RMTs is [(M, H, H), (L, H, M), (M, H, H), (L, H, H)] for each product optimal configuration of machine is found and sequence of operation which gives less idle time of machine *i.e.* less number of reconfiguration in machines is 1342.

As the fitness increases corresponding takt error decreases in each generation to give optimal configuration of machines as depicted in figure 2.

![Error Curve](image)

**Figure 2.** Error curve during GA convergence.
5. Conclusion
This paper presented a manufacturing system model where RMTs are used to achieve flexibility in capacity. A prime lean concept of takt time is considered to get synchronized production for a pull based system. Industries today face the challenge of increased market volatility and have to deal with rapidly changing demands and delivery times. The optimum configuration of RMT capacity and determination of the correct sequence of processing the product are addressed in the present work. A GA approach is effectively made to find solutions for the given problem. The decreasing trend for the error curve with every generation validated the convergence of GA and the optimal solutions obtained.

This work can be extended to include other lean characteristics like balanced work schedule and machine cells for more integrative models. GA results and computational complexities can be compared with other existing meta-heuristics.

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