A Decision Support Tool for Resource Allocation in Batch Manufacturing

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Abstract - *A decision support tool for production planning is discussed in this paper to perform the job of machine grouping and labour allocation within a machining line. The production plans within the industrial partner have been historically inefficient because the relationship between the cycle times, the machine group size, and the operator's utilisation hasn't been properly understood. Starting with a simulation model, a rule-base has been generated to predict the operator's utilisation for a range of production settings. The resource allocation problem is then solved by breaking the problem into a series of smaller sized tasks. The objective is to minimise the number of operators and the difference between the maximum and minimum cycle times of machines within each group. The results from this decision support tool will be presented for the particular case study.*

Keywords: Production planning, batch manufacturing, simulation, decision support, resource allocation.

1 Introduction

Efficiency and productivity are vital in manufacturing to continually improve financial performance. This paper investigates these issues with a production planning methodology examining the introduction of high performance Computer Numerically Controlled (CNC) machines into a new plant. In particular, this research examines how resources are allocated when human/machine interaction is considered during operation. There are various production planning methods that have been extensively researched in the literature. The purpose of this research, however, is to solve the task of resource allocation, using a methodology that can be applied and used by a variety of production personnel in a desktop computer environment. In this research it is believed that the complex task of job and resource allocation in a group of flexible machining cells can be solved by partitioning the task into a series of smaller objectives. This paper will show how such an approach can be successfully applied to this type of problem, and in doing so provide a decision support tool for the industry partner's production planners. The manufacturing facility under investigation is a series of machining lines laid out so as to maximize the utilisation of machine capacity, but not necessarily the labour requirements. The machining lines form part of a larger manufacturing facility that manufactures and assembles a range of automotive brakes, which are then installed into production line cars and trucks. This manufacturing facility has been laid out along functional lines, due to problems encountered with earlier factory designs focusing on customer-based operations. The aim is to achieve the lowest capital and operational cost possible.

Previous work with regards to resource allocation has focused on two distinct areas of literature, namely Cellular Manufacturing (CM) [1] and Flexible Manufacturing Systems (FMS) [2]. The problem investigated in this research is one of a dedicated FMS, with human material transfer between machines.

Investigation into the resource allocation issues identified in both areas of interest has identified a number of key techniques used to solve the problems encountered. Key amongst these techniques are the mathematical optimisation techniques such as Mixed Integer Programming [3] and goal programming [4]. Often, the problem formulated is of a non-linear form, and so must be linearised in order to develop a reasonable solution. One key problem with such an approach is the time taken to formulate the problem, and then to solve it. Even reasonably sized problems become difficult to solve in reasonable time. A significant development in this area of research was by Stecke [5]. To reduce the complexity of a problem into a more realistic size, the task was partitioned into a number of smaller sub-tasks and solved individually. This methodology has essentially been built upon by many other authors and is part of the rationale behind the partitioning of the problem undertaken during this research.

Other researchers have focused on the application of various heuristic and genetic algorithm based approaches to firstly reduce the size of the solution space and develop efficient methods for determining the optimal solution [6, 7]. Some of these methods have provided insights into how this problem can be successfully formulated and solved, through an examination of the specifics of the case study, and the methodology then extended to solve a broader class of problems.

2 Manufacturing Facility

The industrial partner manufactures a range of automotive brakes, using aluminium brake calipers and a cast iron bracket as the major components. A brake caliper is the structure around which the automotive brake is designed and housed. Calipers are manufactured in three separate, discrete stages; casting, machining and assembly. This manufacturing process is shown in figure 1.2. There are sufficient buffer stocks between each process to allow independent operation for periods of a few days. The machining process, highlighted with a dotted border in figure 1, is the area where the production planning problem exists. This problem is specifically the allocation of labour and jobs to a semi-automated flexible machining system.

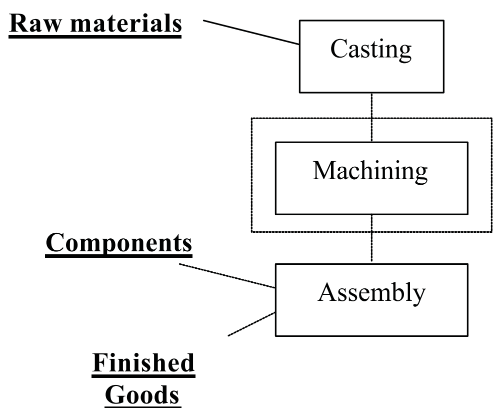

Figure 1: Schematic of overall production process.

There are two part families that are processed within the machining line, a cast iron bracket and an aluminium body. The machining operations consist of forty-eight high speed, flexible CNC machining centres. The forty-eight machines are split up into three discrete 'lines' of machines, arranged with nineteen, fifteen and fourteen machines per line. This is due to the difference in the materials within the two part families, cast iron and aluminium. The two materials have different processing requirements; therefore they must be machined separately. These facilities are quite new and the number of machines per line is based on the current production requirements. There is spare room within the lines for additional machines to be installed should the throughput requirements increase in the future.

Each machine operates independently, and machining is performed in a semi-continuous manner. Each machine is set up with the necessary tooling, software and fixtures for the part type that it's dedicated to producing for the production period. The three lines of machines are grouped separately into cells, where each cell consists of usually four closely positioned machines and an operator and each cell operates independently to other cells. The operator is responsible for loading and unloading the machines within their particular cell of machines. Input and output conveyors are positioned next to each machine. These conveyors transport un-machined and machined parts to and from each machine respectively, via an operator. For each machine within their cell, the operator loads the un-machined parts into the machine, removes the machined parts from the machine and places them on the output conveyor. If the operator fails to attend to each machine in their cell, the cell remains idle.

3 Aims and Experimental Methodology

3.1 Aims

The overall aim was to solve the production planning problem developed within the industrial partner. The aim was to develop:

> A spreadsheet-based decision support tool that could be easily employed by production planners to optimise the utilisation of machines and labour.

In the course of doing so, two questions needed to be answered first. These questions were:

1. What is the maximum utilisation rate allowable for each operator?
2. Is the operational practice of four machines per operator cell the best use of resources?

3.2 Methodology

Before the spreadsheet planner could be developed, the aforementioned questions needed to be answered. A discrete-event simulation model of the machining line was used to answer the second question posed above. The first question was answered through consultation with key personnel within the industrial partner, i.e. it was assumed using empirical knowledge to be 85%. The simulation model has been used to mimic the machining line performance by replicating the identical CNC machines in a commercial simulation package called QUEST. The model was developed such that an operator could load and unload a range of machines from three to six, each potentially producing different parts with different cycle times. A series of experiments were conducted to answer the last question posed above. The result was a matrix of the preferred number of machines in each cell for a range of product cycle times. The endpoint of the simulation experiments was a rule-based matrix, which fed directly into the planning tool.

As stated in the introduction, the key approach to solving the production planning problem was to reduce the size of the problem through partitioning, thus allowing a smaller solution space to be searched. This will be detailed in a later section, but Figure 2 provides an overview of the decision support tool methodology.

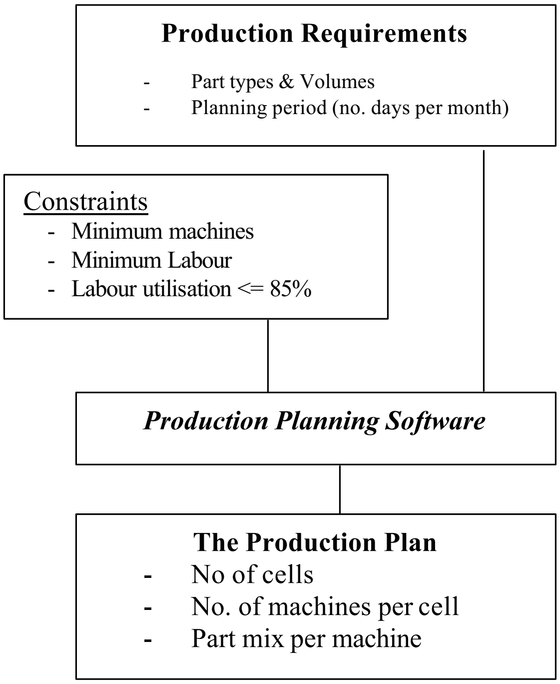

Figure 2: Decision Support Tool overview

The approach is to use the results from the simulation, along with key input data such as part cycle times and volumes, to develop a job list for the upcoming planning period. The matrix of cell groupings can then be used to reduce the possible number of configurations, and an optimum solution found by searching through a much smaller solution space. This approach makes it amenable to developing the production planner in a spreadsheet as an off-line decision support tool.

4 Simulation and Results

4.1 Simulation structure

The basic construction of the simulation model was to replicate the one base machine into a cell ranging from three to six machines, separated by the appropriate distances between each machine, and located such that every second machine was opposite the first machine and separated by the walkway distance. An operator walk path was then laid out, so that the operator could move from one machine to any another machine in the cell. The supply of input parts is assumed infinite, and these arrive via a small conveyor next to each machine. Finished parts are placed on another conveyor next to the input conveyor, from where the parts are removed from the simulation. A graphical comparison of the plant configuration and the simulation configuration is given in Figure 3 and 4.

Figure 3: Plant configuration

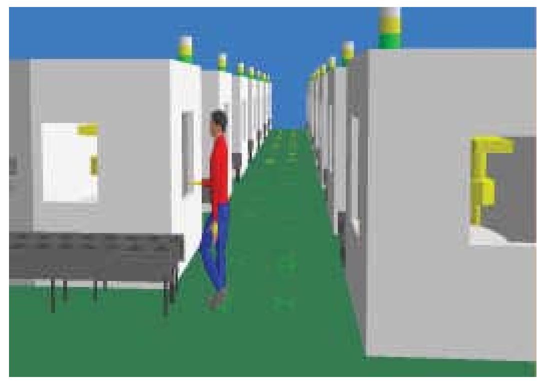

Figure 4: Simulation model

4.2 Simulation Inputs

A range of inputs were collected from the plant records and key personnel from within the industrial partner. The inputs for the system included:

Preventative Maintenance schedules.

Tool changes (replacement of worn tools)

Tool condition monitoring alarms (detect faulty tools)

Machine failures

Coolant system failures

The preventative maintenance schedules were obtained from the manufacturers specifications and were a mix of monthly, three monthly and annual downtimes. The other three sets of downtimes were stochastic and modelled as triangular distributions with upper and lower limits.

4.3 Operator and Machine Logics

QUEST has an in-built programming language so that custom logics can be developed to mimic the behaviour observed in the manufacturing plant. Custom logic was therefore developed for the machines, and the operators, both of which will be explained briefly.

Essentially all that the machine does is wait for a part to be loaded, close the doors, and begin the machine cycle. There are, however, two sections of the machine. In the front section, parts are loaded or unloaded and in the back, the parts are machined, with a rotating table moving the parts between the two sections. A number of software modules were written using signals and wait commands, such that the modules synchronise with each other to operate as desired. The task of the operator is to load and unload parts into their assigned machines in a cyclic order. Each machine requires loading and unloading manually using a human operator. The operator's task when the door automatically opens is to:

Pick up two parts from the input conveyor

Place them into the fixture inside the door

Pick up the two completed parts from unloader

Place the two completed parts onto the output conveyor.

A default operator walk path has been defined so that the operator moves in a cyclic pattern, and only tends to the loading and unloading of a machine when there is a requirement for this. This logic has been programmed into the walk path of the operator in the simulation.

4.4 Simulation validation

A series of simulation validation exercises were performed to ensure the model was giving reasonable outputs. A base model was developed, without any stochastic effects, and the output from this model was as expected for a case with only planned downtime. When the stochastic downtime was included in the model, the output was averaged at 99 parts per hour, for four machines, which was in close agreement with the actual output for a cell in the plant. The validation exercises gave the simulation model some reasonable credibility when attempting to change the operational philosophy within the plant.

4.5 Simulation results

In order to answer the question of whether it's efficient to operate with four machines per operator, a series of 60 simulation experiments have been run, each combining a unique number of machines (ranging from 3 to 7) with a range of consistent cycle times for each machine (ranging from 150 to 260 seconds). In this way the average operator utilization, over a six month simulated production run, can be determined from the simulation model. The results can then be tabled in a matrix, as shown in Table 1. From this table key conclusions can be drawn, given that the average operator utilization shouldn't exceed 85%.

Table 1 – Optimum cell configuration results

Cycle Time for each machine in cell (secs)	No. of Machines				
	3	4	5	6	7
150	63%	80%	n/a	n/a	n/a
160	59%	75%	n/a	n/a	n/a
170	56%	70%	90%	n/a	n/a
180	53%	67%	87%	n/a	n/a
190	50%	63%	83%	n/a	n/a
200	47%	60%	79%	n/a	n/a
210	45%	58%	75%	90%	n/a
220	43%	55%	72%	86%	n/a
230	41%	53%	69%	82%	95%
240	40%	50%	67%	78%	94%
250	38%	49%	63%	74%	92%
260	37%	47%	60%	70%	91%

The above results indicate a four machine cell is best suited for average cycle times between 150 and 180 seconds. A five machine cell is best suited for cycle times that average between 190 and 220 seconds, and a six machine cell is best suited for cycle times between 230 and 260 seconds. A cell that contains only three machines is acceptable; however this will mean that the operator is poorly utilised. If more than six machines are used in a cell, then the operator will be overworked, which is not acceptable. So the simulation model has answered the critical question of the cell size as a matrix rule base.

5 Decision Support Tool

There are various approaches used to solve part mix, cell formation and resource allocation problems. The difficulty when using techniques such as mathematical optimisation, simulation or genetic algorithms is that a significant amount of effort goes into deriving the optimisation criteria, and significant computational overhead is required to calculate a solution. To overcome this, authors such as Stecke [5] partition the problem into smaller sub problems; where separate formulations are used to solve each sub problem independently. This reduces the difficulty in formulating the problem and reduces the potential search space when finding an optimum solution. This section will show that by understanding the problem in more detail, a series of sub problems can be generated, and solved separately. A methodology has been developed to solve problems that require determining the optimum cell sizes and allocation of resources. This methodology is detailed for this case study in Figure 5, with the partition occurring in the potential configurations stage.

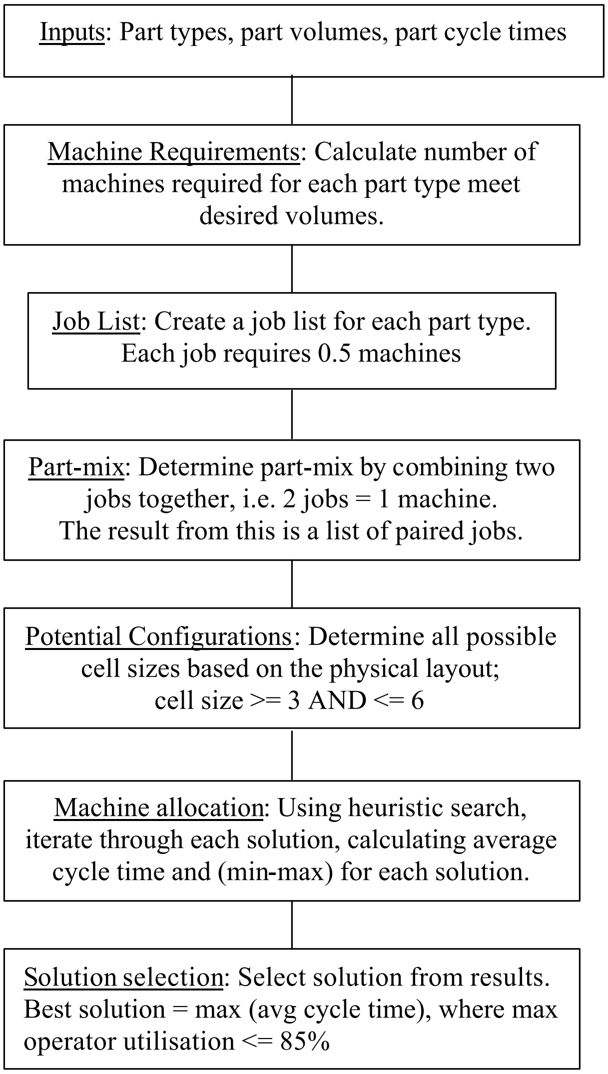

Figure 5: Flowchart of decision support tool.

5.1 Bracket Machining Line

This planning methodology has been applied to one particular line of the three lines identified in section 2, the machining of the cast iron brackets. This line has nineteen machines, so given that the range of cell sizes is from 3 to 6 machines, there are only 6 possible cell combinations, as shown in Figure 6.

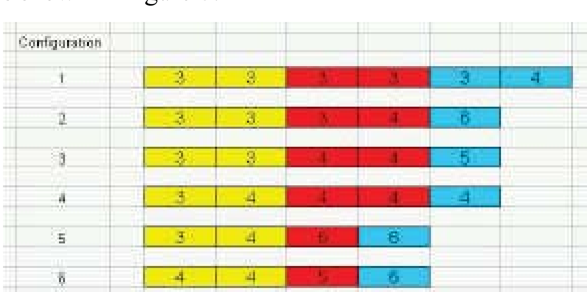

Figure 6: Possible combinations for bracket machining line.

By pre-determining the cell sizes from understanding the physical limitations of the problem, the size of the solution space has been greatly reduced. When the heuristic search was applied, with a given set of demand parameters from the industrial partner, the number of possible combinations is such that most solutions can be evaluated and a good solution obtained. In this particular example, the evaluation of the six possible combinations given in Figure 6 produced results summarized in Table 2.

Table 2: Results from decision support tool for bracket line.

Config.	cell1	cell2	cell3	cell4	cell5	cell6
1	59%	59%	59%	59%	56%	63%
2	59%	59%	59%	70%	100%	
3	59%	59%	70%	70%	87%	
4	59%	75%	70%	70%	63%	
5	59%	75%	100%	100%		
6	75%	75%	100%	100%		

Table 2 provides the results from the decision support tool as average operator utilisation percentages for each of the cell groupings identified from Figure 6. For example, configuration 6 has average utilisation percentages of 75%, 75%, 100% and 100% across the four cell sizes of 4, 4, 5 and 6 respectively. Obviously, given that the operator utilisation exceeds the upper bound of 85% in two cells implies that this configuration is not suitable for implementation in practice. In fact, only two of the given configurations obtain results where one cell doesn't exceed the upper bound of 85% operator utilisation. This is summarized in Table 3, where the average and peak operator utilisation across all cells is determined. If the peak operator utilization is greater than 85%, the result is not applicable. From Table 3 it is clear that configuration 4 provides the best cell configuration for the bracket machining line. The decision support tool also determines the location of each part on each machine for the length of the planning period, so the production personnel can use this information directly on the line.

Table 3: Summary of results for bracket line.

	Average operator utilisation	Peak operator utilisation	Effective Operator utilisation
Configuration	59%	63%	59%
Configuration	69%	100%	n/a
Configuration	69%	87%	n/a
Configuration	68%	75%	68%
Configuration	83%	100%	n/a
Configuration	85%	100%	n/a

5.2 Body Machining Line

The decision support tool was also applied to the body machining line, which is broken into two separate lines for reasons of space availability. These lines contain 29 CNC machines and allows for 16 possible combinations. The caliper body is made of aluminium, and the machining cycle times are generally longer than for the bracket. The generally longer cycle times has meant that the cell size for each operator is generally larger than for the bracket machining line.

Table 4: Summary of results for Body Machining Line.

	Average operator utilisatio	Peak operator utilisation	Effective Operator utilisation
Configuration1	47%	56%	47%
Configuration2	52%	78%	52%
Configuration3	53%	67%	53%
Configuration4	52%	67%	52%
Configuration5	51%	56%	51%
Configuration6	59%	78%	59%
Configuration7	60%	78%	60%
Configuration8	61%	72%	61%
Configuration9	59%	78%	59%
Configuration10	60%	69%	60%
Configuration11	59%	78%	59%
Configuration12	59%	67%	59%
Configuration13	69%	82%	69%
Configuration14	70%	78%	70%
Configuration15	58%	67%	58%
Configuration16	68%	78%	68%

The summary results from the body machining line are presented in Table 4. Of the 16 combinations, most allow for an acceptable solution, due to the longer cycle times, with configuration 14 providing the highest average operator utilisation. In practice, configurations 13, 14 and 16 all provide reasonable average operator utilizations and so the final production plan adopted would be at the discretion of the production manager. Overall, the decision support tool has developed a production plan that reduces the number of operators from seven to six per shift for the body machining line, compared with the staffing levels currently used. Such a saving is worth the effort of developing the tool in the first instance.

6 Conclusion

This paper has highlighted the development of a decision support tool to help production personnel examine and allocate human and capital resources in a batch machining line. By partitioning a large solution space, through an understanding of the constraints in the system, the authors have shown the development of a tool that allocates part production to cells of machines, operated by a human. A simulation model was developed to solve a key question in the evolution of the tool, and suggested that for longer cycle time products, the current manning of cells was inefficient. From here, the decision support tool was able to demonstrate a reduction in the number of operators required for the machining lines from 12 to 11 personnel per shift.

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