

## OPTIMISATION OF A FLEXIBLE MANUFACTURING SYSTEM THROUGH THE APPLICATION OF GREEDY KNAPSACK HEURISTIC

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### ABSTRACT

The global manufacturing industry is currently facing intense competitive pressure that requires better efficiency, effectiveness and continuous improvement of the manufacturing systems. Production planning in flexible manufacturing systems is crucial for the efficient organisation of production resources to ensure economic effectiveness and meet schedule requirements without violating capacity constraints. The objective of this paper is to develop a cost-effective assignment of parts to a flexible manufacturing system (FMS) through the application of Greedy Knapsack heuristic. A production planning problem was formulated, the objective function and associated constraints were stated and an Excel based tool was developed to generate solutions Greedy Knapsack heuristic. The tool would assign the best-selected parts to the semi-automated FMS in an optimal manner to the production plan. The sample computational results were presented for Greedy Knapsack heuristic, and conclusions were drawn for the flexible manufacturing system.

**Keywords:** flexible manufacturing system; Greedy Knapsack heuristic; optimisation

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## 1 INTRODUCTION

The automotive manufacturing industry is one of the competitive industries since global forces have put due pressure on manufacturers to derive a delicate tradeoff between profitability and cost effectiveness [1]. Some automotive manufacturers shed off the first-tier market thereby giving second-tier manufacturers an opportunity to compete for more contracts [2]. Second-tier suppliers re-vitalised their business processes to increase part quality in order to win these contracts, while improving process stability, cost per part, and reliability. A flexible manufacturing system (FMS) that is fully automated and characterised by reliable machining centres would render automation to be possible. Flexible manufacturing systems have the potential to enhance the quality and productivity of products and would change the dynamics of the employees in a firm and thereby create supplementary, higher-order jobs. It is imperative for organisations to embrace FMSs to handle rapid market fluctuations, lower volume and lower production costs as well as increase competition on the international platform [3]. Additionally, an FMS would aid an organisation in attaining enriched market response, and enhance flexibility in production quantities and product quality. Flexible manufacturing systems also have the potential to satisfy the customer needs with ease, reduce production time, costs incurred and reduce labour cost. It is against the backdrop of increased operational costs and heightened product defects that the case in point automotive component manufacturer was prompted to investigate its effectiveness, striving to improve operational performance. The objective of this paper is to develop a cost effective assignment of parts to a flexible manufacturing system (FMS) through the application of Greedy Knapsack heuristic.

## 2 RELATED LITERATURE

An FMS is an array of automated processing machines that are interconnected by a material handling system and a central computer system to coordinate the production activities [4]. The manufacturing process of an FMS is characterised by a blend of workstations and possibilities of routing paths, provided by a material handling system and automatic inspection stations whereby the rejected parts must return for further processing while approved parts exit the FMS. An FMS can process different part types concurrently at several workstations that can be adjusted automatically when unexpected variations in the volume of orders or in the mix occurs [5]. Due to their ability to economically process intermediate volume and product variety, cellular layouts are preferred for FMS.

FMSs are characterised by machine tools that integrate the machine and controllers, the tool and the part to be processed. The fundamental elements of the FMS would include machine base, tools and automatic tool changer, parts handling devices, logic-programmable commands and sensors, as well as drive units and controls [6]. The setup in FMS workstations is automatic and instantaneous, requiring minimal or no human attention on the CNC machine tools that are equipped with tool magazines to perform multiple sequential operations such as turning milling, etching and drilling.

The material handling system for an FMS is characterised by pallets and containers, transported by conveyors or automated guided vehicle systems (AGVS). The AGVS would reduce labour cost, accidents, and improve the speed and accuracy of transportation in FMSs since they are unmanned and would follow a guided inductive path in automated facilities [7]. Under the coordination of a central computer system, the main functionalities of AGVS in FMSs include traffic management to avoid collisions, optimisation of the route, and loading and unloading of materials. Conveyors transport standard loads through fixed paths that are shaped by rollers, casters, sloping mats, chains to complement AGVS, and provide bi-directional horizontal and vertical transport and direction changes. Robotic arms are also used in material handling systems and an industrial robot can be programmable, characterised by anthropomorphic features such as response to sensory stimuli, arm resemblance, decision-making ability and communication with other machines [8]. The main tasks performed by

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robots in flexible manufacturing systems for the automotive industry are welding, painting, palletising, handling, and assembling. Another key feature of FMS is an automated storage and retrieval system that comprise storage structures, transelevators and stacker cranes suitable for receiving and storing standardised loads from pallets and containers [6]. FMSs are also characterised by automated inspection stations that perform faster and more reliable final quality inspection procedures using automated devices and software tools to execute quality verification of parameters, such as shape of parts and dimensions [9].

There are different forms of flexibility that characterise an FMS and these include material handling flexibility, process flexibility, machine flexibility, product flexibility, volume flexibility and operation flexibility [10]. Regarding material handling flexibility, the path followed by the product or part between machines is of concern, while process flexibility embraces flexibility in a particular part to be processed by different types of processes. Machine flexibility is concerned with machine capability to accommodate the different product mix. Routing flexibility pertains to different achievable routes that a part or product can follow while operation flexibility is concerned with the varying processing plans with respect to production of a part [11]. Expansion flexibility relates to the capacity of production and without the variation in capital of the equipment, production flexibility can also be achieved for all types of parts.

Considering the analysis of 0-1 knapsack problems, Ezugwu et al. [12] presented results of meta-heuristic optimisation algorithms, namely, simulated annealing (SA), genetic algorithms (GA), dynamic programming, branch and bound, Greedy algorithm, and a hybrid GA-SA. The results demonstrated superior performance from the hybrid algorithm when compared with individual algorithms, show-casing that hybrid algorithms can be deployed as an alternative to solve 0-1 knapsack problems. Singh et al. [13] conducted a critical review of scheduling machine loading problems in FMS as a manufacturing strategy for obtaining an optimal balance between productivity-flexibility requirements. The FMS problem was concerned with part type selection, production ratio, machine grouping, resource allocation and loading scenario. Binghai et al. [14] developed a heuristic for loading and batching problems in an FMS with the objective to minimise the number of tool changes and reduce line imbalance considering that machine loading and part type selection are key problems in production planning of FMS. Windmann et al. [15] also developed a model-based routing approach for an FMS with substitute routes for the parts that underwent several processing steps, whereby each processing step could be accomplished on alternative workstations. The proposed heuristic would derive energy efficient and fast routes for the parts in the conveying system leading to reduction of energy consumption in the FMS. This study adopted the Greedy algorithm since it has the advantage of simplicity and has less computational cost compared to other heuristic algorithms. The use of the Greedy algorithm for local or instant results aids in deriving better results.

### 3 RESEARCH METHODS

#### 3.1 Background

The case in point automotive component manufacturer produces different types of crankshafts in batch mode for engines to satisfy local orders. Root cause analysis was conducted to identify the problems of waste in existing crankshaft fabrication process and it was noted that high cycle time, unnecessary additional processing time, more workers than required and too much work-in-process and scrap could be the main sources of increased operational costs. The scope of this study is a semi automated flexible manufacturing cell (FMC) that was used to produce three different types of crankshafts. The quantitative analytical modelling approach was adopted for the optimisation of a flexible manufacturing system. Initially, a deterministic bottleneck model was deployed to U-shaped layout FMS and the research approach commenced with identifying the equipment and number of workers for the semi automated flexible manufacturing cell. A work study was thereafter conducted to establish the the station

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processing times, part mix for FMC, operation frequency and the routes for the part styles. The subsequent steps were characterised by identifying bottlenecks through computation of station workloads against the number of servers and thereafter assessing the utilisation of the FMC. Lastly, after noting the opportunity to improve the cell utilisation, the Greedy Knapsack heuristic was deployed to assign some additional parts to the FMS.

### 3.2 Bottleneck Analysis

Table 1 shows a summary of the description of activities and number of servers, the crankshafts are loaded and unloaded by one human worker and thereafter machined by two automated stations followed by oil hole drilling at two servers and lastly taken for manual grinding. In this sense, servers refer to number of machines that have the capability to perform the same operation. The mechanised carts move tote bins with crankshafts as the primary material handling system between FMC stations.

**Table 1: Description of activities and number of servers**

Station	Description	Number of servers
1	Load and unload	1 human worker
2	Turning	2 servers
3	Oil hole drilling	2 servers
4	Grinding	1 human worker
5	Transport	2 carriers

A work study was conducted and the results for the part styles as well as the routes followed were established. Table 2 shows the station processing times and part mix for FMC and the operation frequency is 1 for all the operations. All the parts would follow the sequence: 1 → 2 → 3 → 4 → 1 and the mean transfer time of the mechanized cart between stations was established as 2.5 minutes.

**Table 2: Station processing times and part mix for FMC**

Part	Part mix	Station 1	Station 2	Station 3	Station 4	Station 1
		Processing time in minutes				
Crankshaft X	0.25	2	2.5	1.5	4	3
Crankshaft Y	0.45	2.5	3	2.2	7	3
Crankshaft Z	0.3	1.5	2	1.5	5	3

It was therefore imperative to establish the bottleneck station in the FMC, also considering that the material handling system could also bottleneck the process. It was also important to establish the overall production rate of the system and if any recommendations could be made to improve the efficiency or reduce the cost of operating the FMC by addition of other parts that could be processed by the system. The workload for the stations was computed as:

$$WL_i = \sum_j \sum_k t_{ijk} f_{ijk} \rho_j \tag{1}$$



where  $t_{ijk}$  is the processing time,  $i$  refers to station,  $j$  is part  $k$  is the sequence of operations for the process route,  $f$  refers to operation frequency, and,  $p$  refers to part type or style.

The material handling system that was used to transport the crankshafts within FMC was regarded as a special workstation and designated as station  $n+1$ . The workload for the special station was computed as:

$$WL_{n+1} = n_t t_{n+1} \tag{2}$$

where

$$n_t = \sum_i \sum_j \sum_{k-1} f_{ijk} p_j \tag{3}$$

and for a given process routing,  $t_{n+1}$  is average transportation time needed to convey a crankshaft from one workstation to another.

### 3.3 Assignment Of Parts To Fms

Thereafter, a Greedy Knapsack heuristic was deployed for cost effective assignment of parts to the FMS, through ranking or ordering the part types and selecting the part type while ensuring that inclusion was feasible. Greedy heuristics can simply solve optimisation problems by choosing the most immediately attractive parts that could be added to the FMC to enhance its effectiveness and reduce operational costs. The savings per period in this case, per month were computed through the following steps:

Define:

$$p_i = \frac{\text{hours}}{\text{unit}} \times \frac{\text{unit}}{\text{period}} = \frac{\text{hours}}{\text{period}} \tag{4}$$

$$s_i = \frac{\text{Savings}}{\text{unit}} \times \frac{\text{unit}}{\text{period}} = \frac{\text{Savings}}{\text{period}} \tag{5}$$

$$\frac{\text{Savings}}{\text{unit}} = \text{Purchase cost} - [\text{material cost} + \text{processing cost}] \tag{6}$$

where

$$\text{Processing cost} = \text{Cell overhead rate} \times \text{Production time} \tag{7}$$

and

$$\frac{\text{Savings}}{\text{hour}} = \frac{\text{Savings}}{\text{period}} \div \frac{\text{hour}}{\text{period}} = \frac{s_i}{p_i} \tag{8}$$

The Knapsack Problem was then defined as:

$$\max \sum_{i=1}^n s_i x_i \tag{9}$$

$$\text{subject to constraints } \sum_{i=1}^n p_i x_i \leq P \text{ and } x_i \in \{0,1\}$$

where  $P$  = Production capacity,  $x$  = Decision variable for adding parts to FMC

Equation (1) sums the savings resulting from assigning part types to FMS. Equation (2) fills the knapsack with the most valuable items (Largest  $s_i$ ) without violating its size  $P$ .

The Greedy Knapsack heuristic followed two basic steps that are:

**Step 1.** Order part types  $i$  such that

$$\frac{s_1}{p_1} \geq \frac{s_2}{p_2} \geq \dots \dots \dots \geq \frac{s_n}{p_n} \tag{10}$$

**Step 2.** For = 1 to  $n$

Select part type  $i$  if  $s_i \geq 0$  and inclusion is feasible.



Feasible inclusion means that no savings/unit < 0 and no  $p_1 > P$ .

#### 4 RESULTS AND DISCUSSION

The results for the average workload for a given station were computed as the average total time spent at the station by each of the crankshafts, and are thus shown below:

$$WL_1 = (2+3)(0.25 + 0.45 + 0.3) = 5.0 \text{ min}$$

$$WL_2 = 2.5(0.25)(1.0) + 3(0.45)(1.0) + 2(0.3)(1.0) = 2.6 \text{ min}$$

$$WL_3 = 1.5(0.25)(1.0) + 2.2(0.45)(1.0) + 1.5(0.3)(1.0) = 1.8 \text{ min}$$

$$WL_4 = 4(0.25)(1.0) + 7(0.45)(1.0) + 5(0.3)(1.0) = 5.7 \text{ min}$$

$$WL_5 = 2.5(4) = 10.0 \text{ min}$$

Station 5 was characterised by the highest work load while station 3 had the least workload. The production rate of the FMC was noted as being constrained by the station with highest work load per server, that is the the bottleneck station.

**Table 3: Summary of workload to number of servers ratio**

Description	Station	WL <sub>i</sub> /s <sub>i</sub> ratio	
Load and unload	1	5.0/1 = 5 min	
Turning	2	2.6/2 = 1.3 min	
Oil hole drilling	3	1.8/2 = 0.9 min	
Grinding	4	5.7/1 = 5.7 min	← Bottleneck
Transport	5	10.0/2 = 5.0 min	

Table 3 shows a summary of workload to number of servers (s<sub>i</sub>) ratio and the results indicate that the grinding operation is the bottleneck station in the FMC. The average production rate of the FMC was computed as:

$$R_p^* = \frac{s^*}{WL^*} = 1/5.7 = 0.176 \text{ crankshafts/min} = 10 \text{ crankshafts/hr}$$

Excluding the material transport system, the proportion of time that the servers at the station are working and not idling was computed as mean utilisation, U<sub>i</sub> of each workstation:

$$U_1 = (5.0/1)(0.176) = 0.884 = 88\%$$

$$U_2 = (2.6/2)(0.176) = 0.2278 = 23\%$$

$$U_3 = (1.8/2)(0.176) = 0.1606 = 16\%$$

$$U_4 = (5.7/1)(0.176) = 1.0 = 100\%$$

These results demonstrate gross under-utilisation of the oil hole drilling that was found to have a utilisation of 16%, as well as under-utilisation of the turning station that had a utilisation of 23%.

The average station utilisation for the FMC was computed as:

$$\bar{U}_s = \frac{\sum_{i=1}^n s_i U_i}{\sum_{i=1}^n s_i} = \frac{1(0.884)+2(0.228)+2(0.161)+1(1.0)}{4} = 0.665 = 66.5\%$$

The average station utilisation for the FMC displays that there is room to explore automated options for the grinding operation. It is worth noting that grinding applications are generally not cost-effective or practical for automation since they may be characterised by gross part complexity or high product mix. Technological advances have proliferated hence more

potential for automated grinding. However, it is crucial to consider the factors of any abrasive application, including application force, abrasive speed, horsepower, torque requirements, disc backup plates, part temperature, expected life of the abrasive, and the expected part finish. The latest abrasive technology can significantly reduce grinding time, reduce the number of passes and heat generated. It is also worth noting that ergonomics and safety considerations are imperative any manual grinding operation. Hence, automated grinding provides better grinding paths for the grind tool, paths that would be impossible or uncomfortable to perform by human operators. Therefore, with automated grinding, no manual operator is available, hence no need to factor ergonomic considerations in the operation.

Given the room for more utilisation of the FMC, apart from the crankshafts, it was proposed to add some additional parts that could be processed by the FMC and six parts that were initially sourced from a vendor were considered for an automated FMS. The FMC was available 180 hours / period and charged at R400 / hour. The information regarding the purchase price, material cost if made inhouse and demand was pulled from the organisation’s database and Table 4 shows a summary of the part purchase price, material cost and demand.

**Table 4: Part purchase price, material cost and demand**

	Part type					
	1	2	3	4	5	6
1. Purchase price / unit	1500	1200	2000	1000	2500	650
2. Material cost	300	250	1000	400	1000	200
3. Demand / period	70	40	35	50	25	20
4. Hours / unit	1	2	3	1	2	1

Using the row runbners, we need to compute the following:

5. Savings / unit = (1) - [(2) + R400 × (4)]
6. Hours / period,  $p_i$  = (3) × (4)
7. Savings / hour = (5) / (4)
8. Savings / period = (5) × (3)

The numbers in brackets, 1 to 5 refer to the variables or expressions indicated in the first column of both Table 4 and Table.

An Excel spreadsheet was used to determine necessary data for the heuristic assignment problem as shown in Table 5.

**Table 5: Excel spreadsheet summary for computational results**

	Part type					
	1	2	3	4	5	6
1. Purchase price / unit	1500	1200	2000	1000	2500	650
2. Material cost	300	250	1000	400	1000	200
3. Demand / period	70	40	35	50	25	20

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	Part type					
	1	2	3	4	5	6
4. Hours / unit	1	2	3	1	2	1
5. Savings / unit	800	150	-200	200	700	50
6. Hours / period, $p_i$	70	80	105	50	50	20
7. Savings / hour	800	75	-	200	350	50
8. Savings / period, $s_i$	56000	6000	-	10000	17500	1000
9. $s_i / p_i$	800	75	-	200	350	50

Applying the Knapsack heuristic to optimise the utilisation of the FMC:

**Step 1** - Order part types in descending order of savings per hour to give:

$800 > 350 > 200 > 75 > 50$ ; excluding negative values

Hence the sequence is {1, 5, 4, 2, 6}

**Step 2** - Select part types while ensuring that inclusion is feasible without violating capacity constraints:

1<sup>st</sup>, Part 1 is assigned, with resource usage (6) = 70 hours

2<sup>nd</sup>, Part 5 is assigned, with resource usage = 70 + 50 = 120 hours

3<sup>rd</sup>, Part 4 is assigned, with resource usage = 120 + 50 = 170 hours

4<sup>th</sup>, Part 2 is not assigned, with resource usage requires 80 hours (only 10 hrs available)

5<sup>th</sup>, Part 6 is not assigned, with resource usage requires 20hrs (only 10 hrs available)

Hence only parts 1, 5 and 4 are added to the FMS using 170 hours out of 180 hours available.

Savings is row (5) × row (3) i.e.

$$\sum s_i = s_1 + s_5 + s_4 = [800 \times 70] + [200 \times 50] + [700 \times 25] = R 83 500$$

These results demonstrate that the organisation could improve the effectiveness and utilisation of the FMC, and concurrently derive some savings by addition of parts that could be processed by the FMC.

## 5 CONCLUSION

A quantitative analytical modelling approach, using a deterministic bottleneck model was deployed to U-shaped layout FMS. These results demonstrated that the grinding operation was the bottleneck station and the process was characterised by gross under-utilisation of the oil hole drilling and turning stations of the FMC. A cost effective assignment of parts to a flexible manufacturing system was accomplished through the application of Greedy Knapsack heuristic. The results also demonstrated that there was room for improvement with regards to the effectiveness and utilisation of the FMC, and concurrently derive some savings by addition of parts that could be processed by the FMC. Further research would embrace digital twin manufacturing paralleled with 5G to optimise operations for automotive component manufacturers.



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