Division of Research
School of Business Administration
The University of Michigan

October 1989
Revised, September 1990

PLANNING AND SCHEDULING APPROACHES TO OPERATE A PARTICULAR FMS

Kathryn E. Stecke
The University of Michigan
School of Business Administration
Ann Arbor, Michigan

Working Paper No. 620B

ABSTRACT

This paper contains a detailed description of a thirteen machine COMAU FMS expected to be operational in Torino, Italy. The monthly and daily problems that need to be addressed and the approaches that are suggested to operate this system efficiently are detailed. The trickier problems and constraints are those of tool management, especially tool loading. Detailed tooling data and their analysis are presented in the Appendix.

The complete spectrum of operational problems addressed range from aggregate planning to detailed scheduling, including fixture and inventory management. Breakdown situations are also addressed.

1. INTRODUCTION

An FMS in Italy is expected to consist of eleven COMAU MSR-15 CNC machine tools, two Rotohead indexers, two washing stations, two inspection robots, six AGVs, and four L/UL stations. Each CNC has one input and one output buffer. After partial processing on the FMS, parts are batched to visit a manual workstation several times.

The aims of this paper and its specific contributions include the following. First, it describes the parameters and constraints of a particularly complex FMS. Then, the actual FMS planning and operating problems that will need to be addressed are described in all detail. Several suggestions of how such a system should be operated are given. The complexity and levels of detail that need to be addressed in order to operate it effectively are provided. The need to use OR modeling and analysis tools is shown. The detailed tooling data and its analysis are presented, which helps to simplify the loading problems. The relevant tooling information can be contained in a Table to be used to help re-solve loading problems manually when this may be required.

In the remainder of this section, some details of the FMS are provided. §2 provides additional constraints and operating facts for the FMS. Initial useful calculations are provided. The operating problems are outlined in §3. Suggested solution procedures for these problems are in §4. The procedures need to deal with given and changing monthly and sometimes daily production requirements. Breakdown considerations are also discussed in §5. An Appendix contains the tooling data and its analysis.

The FMS is planned to work three shifts to initially make five part types of four car and van engines. Then the parts proceed to four engine assembly lines, after undergoing an intermediate subassembly. There may be more variants of these part types (probably using the same fixtures) in the future. There will probably not be more engine types. These part types are described in Table 1. Part types 2 and 3 will be subassembled together. Part type 5 consists of the left and right parts of a cylinder head.

The parts are aluminum. The cylinder heads contain some cast iron pieces. The mix can vary daily for each engine type. Demand is expected to be fairly stable. However,

TABLE 1. Part Type Description.

PART TYPES	DESCRIPTION	ENGINE
1	Intake Elbow	1750 C.C. (16 Valves)
2	Intake Elbow (Lower Part)	Thema F.L. 2000 C.C.
3	Intake Elbow (Upper Part)	Thema F.L. 2000 C.C.
4	Cylinder Head (for a Diesel Engine)	M711 AT.19.2 (4 Cylinders and 8 Valves)
5	Cylinder Head (Left and Right)	Alfa Romeo

in the future the demand may vary a lot, for example, if an engine is used on a new vehicle, light van, or car. This partly depends on the future market.

2. ADDITIONAL INFORMATION ON THE FMS

The FMS will produce according to daily requirements derived from monthly demands. Rush orders for new requirements will also be issued to the FMS. In order to meet expected requirements, an average daily FMS utilization is expected to be about 85%. If now is day n, then information on production for the next day (n+1) is received by the end of the first shift. These requirements are for engine assembly on day n+2.

The four engine assembly lines will work in small batches, at present six parts per batch. Stockouts of other components might occur frequently and the assembly line can then change to a new assembly. This would require only the planning for the new components that would be needed.

The fixturing system is particularly complex. There are nine fixture types required to hold these five part types. Each fixture type has one, two, or three mounts per fixture. Each mount holds one, two, three, or four parts of a particular part type. Each fixture holds from two to eight parts of a particular type. Part types do not share fixtures. This fixture information is provided in Table 2. The number of fixtures to have of each fixture type was determined by using a closed queueing network analysis (see Reiser and Lavenberg [1980], Menga et al. [1984], Cavaillé and Dubois [1982], and Suri and Hildebrandt [1984], for example). The queueing analysis considered the expected processing time per fixture and expected production requirements. Although the assumptions of the model are quite different from the FMS, the results on the numbers of fixtures required of each type was accurate.

TABLE 2. Fixture Information.

PART TYPE	FIXTURE QUANTITY	FIXTURE TYPE	FIXTURE LAYOUT	OPERATION NUMBER
1	5	A-1 (1st, 2nd mount)	(4, 4)	1
2	3	B-2 (1st, 2nd mount)	(4, 4)	2
3	3	B1-3 (1st, 2nd mount)	(2, 2)	3
4	2	P1-4 (1st, 2nd, 3rd mount)	(2, 2, 2)	4, 5
	2	P2-5 (4th mount)	(3)	6
	1	P3-6 (5th mount)	(4)	7
5	12	P1-7 (1st, 2nd, 3rd mount)	(1, 1, 1)	8, 9
	4	P2-8 (4th mount)	(2)	10
	3	P3-9 (5th mount)	(2)	11

Table 2 can be read as follows. For example, fixture type 1 (A-1) holds four parts on the first mount and four parts on the second mount, all eight of the same part type (1). The processing of these eight parts constitutes operation number 1. Four parts of type 1 are fixtured onto the four positions for the first mount. After processing on the FMS, the pallet/fixture combination moves to the L/UL station and the four parts are moved to the four positions on the second mount of the same fixture and four new raw castings replace those previously on the first mount. This describes the processing of part type 1 until its requirements are met. It takes about 5 minutes on a L/UL station to refixture these parts. Since all eight parts move through the system together, this is a single "operation" (1).

Usually, processing time is defined for an operation. However, here the processing time is for each fixture use (and hence, for one to three mounts), since it is a fixture that will move from machine to machine.

Similarly, for part type 4 (cylinder heads) and using fixture type P1-4, there are two parts on each of the first three mounts. Each cylinder head requires two additional fixture types (5 and 6) of one mount each to process the part.

Table 3 provides an initial allocation of operations to the machines, suggested by a previous consultant. It attempts to balance workloads given the average daily requirements. The "V" indicates that the part type "visits" (one of) the indicated machine(s). For example, part type 1, the high-volume intake elbow, is initially allocated to machines MSR-4 and MSR-11 for 36.41 minutes per visit (i.e., per "operation"). Dividing by 4, the processing time/part, in two visits on two different mounts, is 9.11 minutes. Parts of types 2 and 3 would visit either MSR-2 or MSR-3 and the first Rotohead. As we shall see in §4, a fixed allocation, such as the initial allocation suggested by Table 3, could cause problems during system operation. We suggest a more flexible means of operation in §4.

The processing of the cylinder head for a diesel engine (fourth part type) is the most complex and is as follows. There are two operations defined to process cylinder heads using fixture type P1-4 (operations 4 and 5 of Table 2). This is because of the initial fixed allocation of operations to machines based on the average daily volume of Table 3. The first, second, and third mounts are assigned to machine MSR-6. The third mount is refixtured to a new fixture of type 5 (P2-5) and the remaining two mounts progress as follows. Completed third mount parts are taken off of a fixture of type P1-4 and accumulated on a tray until its capacity of twelve is attained. An AGV picks up the tray from L/UL-1 for delivery to a station where operations are performed manually for 196

TABLE 3. Part Type/Fixture Mount Initial Machine Allocation.

					Part Type 4			Part Type 5		
	UTIL.	A	B	B1	P1	P2	P3	P1	P2	P3
	—	1/1-2	2/1-2	3/1-2	4/1-2-3	4/4	4/5	5/1-2-3	5/4	5/5
Roto 1	(35%)		6.66 V	2.21 V	10.88 V					
Roto 2	(73%)							14.44 V		
MSR-2, 3	(69%)		24.07 V	31.59 V						
MSR-4, 11	(80%)	36.41 V								
MSR-5	(60%)					50.84 V	22.69 V			
MSR-6	(44%)				17.43 16.33 2 V					
MSR-7, 8	(85%)								45.66 V	21.28 V
MSR-9, 10, 12	(84%)							25.27 24.46 2 V		
L/UL-1, L/UL-2		V			V					
L/UL-3, L-UL-4			V	V		V	V			
Washing		V	V	V	V	V	V			
Inspection					V	V				

minutes per visit (per twelve parts). Then the AGV delivers the tray to L/UL-2 for fixturing for the fourth mount operation using fixture type P2-5, which has capacity to hold three cylinder heads. Following fourth mount operations (currently allocated to MSR-5 in Table 3), twelve heads are again accumulated on a tray to return to the manual station for 196 minutes. The tray returns to L/UL-2 for the fifth mount on fixture type P3-6 which holds 4 cylinder heads. This unusual process flow for cylinder heads is displayed in Figure 1.

Batch-flow processing can be quite complicated in many systems. However, FMS processing is not usually so complex. The various numbers of parts per mount, numbers of mounts per fixture, and fixture limitations require coordination and planning. The details of this production process are described in order to show how complex a

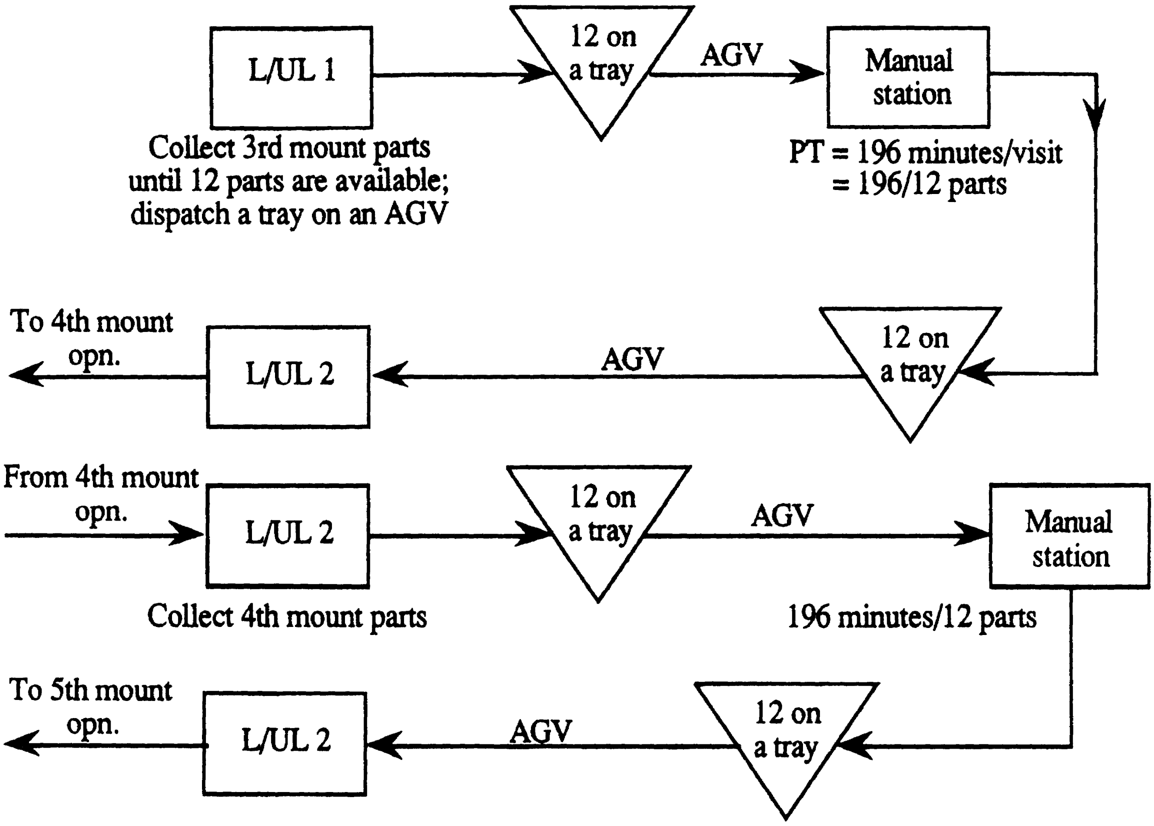

FIGURE 1. Process Flow for Cylinder Heads.

metal-cutting process flow can become. Design engineers worked hard to simplify the processing to this current level of complexity. Factors that needed to be considered included the metal being cut (aluminum), fixturing and processing requirements for accuracy, and machine expenses and potential utilizations. Alternative process flows were suggested, tested, and rejected for various reasons. They would have been inefficient or infeasible or expensive.

3. THE FMS OPERATING PROBLEMS

We define the monthly and daily operating problems that this system needs to solve. One purpose is to evaluate the feasibility of the fixed (and easy to implement) solution of Table 3. Each day, FMS will need to address the following types of problems.

1. **Aggregate Planning**. The daily requirements need to be checked against the available machine capacity, in terms of time, to see whether the demand can be met. The result will be a function of the mix and the number of working machines.

2. **Machine Grouping**. All eleven MSRs are identical. If some subgroups of these are identically tooled, each machine in a subgroup will be able to perform the same operations. Grouped machines that are identically tooled are said to be pooled. It may not be possible to pool sometimes, because of tool magazine capacity constraints. However, it may be possible to duplicate operation assignments and cutters on several machines. These machines are said to be partially pooled.
3. **Machine Loading**. Each operation and its associated cutting tools needs to be allocated to one or more MSRs subject to time and tool magazine capacity constraints. An objective may be to approximately balance the workloads on the machines. Another relevant objective may be to allocate operations so as to meet the daily due date constraints, i.e., to determine a feasible loading.
4. **Fixture Management**. There are no fixture allocation problems as there is no fixture sharing among part types. The fixture problems here will be to determine how many fixtures of each type should be on the system and which fixture type should be input next whenever a pallet/fixture leaves.
5. **Scheduling**. The main scheduling problem will be part input, or dispatching. Parts visit several machines and workstations. Scheduling the flow of the cylinder heads can be tricky because twice, the parts are batched onto trays of twelve to visit manual workstations before returning to the FMS. Also each cylinder head requires five mounts on three different fixture types, all of different capacities.
6. **Inventory Management**. If there is spare time at the end of a day, it should be used to begin the following day's requirements, because of unforeseeable random disturbances such as machine breakdowns. The inventory management policies need to be formalized.

These are the problems that the system will need to address. The main problems are driven by tooling needs and limited tool magazine capacity. An analysis of the initial suggested tooling and grouping solutions given in Table 3 is provided in §4.2. This analysis will demonstrate the infeasibility of such a fixed solution. To overcome the limitations, the following algorithms of §4 are proposed.

4. ALGORITHMS TO SOLVE THE FMS PLANNING AND OPERATING PROBLEMS

In order to formally define the algorithms to solve the FMS problems that were identified in §3, the notation provided in Table 4 is required.

TABLE 4. Notation.

INPUT:

r_i = daily production requirements for part type i, $i = 1,\ldots,5$
i_i = current on-hand inventory of part type i
p_i = processing time for one part of part type i
m = number of working machines: $m \in \{1,\ldots,11\}$
AW = available workload (capacity) from the FMS = 1440 m
f_ℓ = number of available fixtures of type ℓ, $\ell = 1,\ldots,9$
n_ℓ = number of parts per mount on a fixture of type $\ell (\in \{1,2,3,4\})$
po_j = processing time for one machine visit of operation j, $j = 1,\ldots,11$
d_j = number of tool magazine slots required by operation j
t_k = capacity of machine k's tool magazine (= 60 slots for all eleven machines)

PARAMETERS:

Bk = index set of sets of operations
$\bar{B}$ = index subset of Bk such that $|\bar{B}|$ (the cardinality of $\bar{B}$) = p, $p = 2,\ldots,11$
W_{Bk} = number of slots saved when the operations in Bk are assigned to the same machine

OUTPUT:

b_i = daily batch size of part type i
tp_i = total processing time for a batch of part type i
RW = required workload for the day
no_ℓ = number of machine visits per day for the part type that requires a fixture of type $\ell = r_i/n_\ell$
tpm_k = total daily average processing time per machine k
tpo_j = total processing time for the daily requirements for operation j
X_{Ak} = overload (load over balanced) on machine k
X_{Bk} = underload (load under balanced) on machine k
X_{jk} = proportion of total daily required workload of operation j assigned to machine k

$$Y_{jk} = \begin{cases} 1, & \text{if operation j can be done on machine k;} \\ 0, & \text{otherwise.} \end{cases}$$

4.1 Aggregate Planning

Given the next day's requirements, a check has to be made to see if there is enough machine capacity to meet the stated needs of the assembly lines. The current on hand inventory of each part type and the number of working machines need to be considered.

The aggregate planning algorithm to determine the next day's workload requirements is the following. It is similar to the algorithm described in Stecke [1989].

AGGREGATE WORKLOAD ALGORITHM

STEP 1: Calculate $r_i - i_i$, $i = 1,\ldots,5$.

Those part types i such that $r_i - i_i \leq 0$ are not selected to be produced.

Those i such that $r_i - i_i > 0$ are selected to be produced.

The batch size for part type i is:

$$\max\left\{0,\ b_i = r_i - i_i\right\}.$$

STEP 2: Calculate $tp_i = b_i p_i$, for all i.

$$RW = \sum_{i=1}^{5} tp_i$$

$AW = e\ 1440\ m$, where e is a value $\leq$ and near 1.

If $RW > AW$, go to Step 3.

If $RW \leq AW$, STOP.

STEP 3: All required part types cannot be produced because of insufficient machine capacity.

Calculate $RW_i = RW - tp_i$, $i = 1,\ldots,5$.

$$RW = \max_i \left\{RW_i \mid RW_i \leq AW\right\}$$

Otherwise, $RW = \max_i \left\{RW_i\right\}$.

Part type i is not produced.

STEP 4: If RW is still larger than AW, go to Step 3.

If $RW \leq AW$, STOP.

For various reasons, mainly random machine breakdowns, on a given day there may not be enough FMS capacity to produce all requirements. Step 3 suggests selecting one part type at a time not to produce on the FMS. However, at times this may not be possible because of the limited numbers of fixtures available of each type. If some part type is not produced, the corresponding fixtures are not used. It may then be difficult to keep the machines utilized.

To address this situation, Step 3 can be changed so that if there is insufficient capacity, the requirements of all part types are reduced proportionally to remain within capacity. Then an alternative Step 3 is:

STEP 3': The requirements cannot be met, so all requirements are reduced proportionally.

Calculate RW' = a RW, where $a = \frac{AW}{RW} < 1$.

Calculate $tp_i' = a\, tp_i$ and $r_i' = tp_i'/p_i$, where r_i' is rounded down to the nearest integer.

The FMS will produce r_i' parts of part type i.

The remaining requirements will be produced elsewhere.

Step 3' may be necessary because of fixture limitations. In general, Step 3 should be better for several reasons. Firstly, by producing fewer part types, more pooling and/or partial pooling may (but not necessarily) be possible. This tends to help system utilization. Secondly, because of setup time, it might be better for the job shop, which will be producing the part types that the FMS does not have the capacity for, to receive requirements for only one or few part types, rather than all part types at the same time, because of machine set up times.

4.2 Machine Grouping

The initial allocation of operations to machines given in Table 3 allocates each operation to one of six groups of pooled machines of sizes 2, 2, 1, 1, 3, and 2. Table 5 reviews this allocation and also provides the number of tool slots required, total workload,

workload per machine, the number of parts at that processing time, and utilization calculations for each of these six groups of pooled machines for that initial fixed allocation.

TABLE 5. Daily Average Utilizations from an Initial Allocation.

OPN	MACHINES	SLOTS	po_j	WKLD/MAC	r_i	no_ℓ	tpm_k	UTIL-1	UTIL-2
1	4, 11	34	36.41	18.21	235	58.75	1069.84	.74	.80
2, 3	2, 3	51	24.07, 31.59	27.83	85	21.25, 42.5	926.6	.64	.69
4, 5	6	31	17.43, 16.33	33.76	35	17.5	590.8	.41	.44
6, 7	5	46	50.84, 22.69	73.53	35	11.67, 8.75	791.84	.55	.60
8, 9	9, 10, 12	52	49.73	16.58	68	68, 68	1127.4	.78	.84
10, 11	7, 8	23	66.49	33.47	68	34, 34	1137.98	.79	.85

In Table 5, the number of tool slots required for each operation is obtained from the detailed tooling data provided in the Appendix. The po_j are the processing times per fixture ("operation") obtained from Table 3. WKLD/MAC is the average workload per machine required by one fixture. The r_i are the expected daily average requirements. The no_ℓ gives the daily number of machine visits that require the processing time po_j. The tpm_k are the total daily average processing times per machine. Util-1 is the calculated utilization per machine per machine group assuming that the FMS is working three shifts at 1440 minutes/day. Util-2 is the utilization per machine per machine group provided elsewhere by a closed network of queues analysis. It also seems to assume that the FMS is working about 1340 minutes per day on average, or, at about 93% utilization. Util-1 is proportional to Util-2, and considers congestion, or queueing effects.

However, as requirements change over time, so will the utilizations. At times, the fixed allocation of Table 3 will be infeasible. Note that the current allocation, based on average, not actual, requirements is unbalanced. Also, there is a lot of spare space in many machines' tool magazines. We provide an approach to allocate operations to machines in §4.3 to balance workloads irregardless of the requirements.

Pooling machines into groups in advance of production (as the initial suggested allocation does) *can be beneficial* to system performance as it allows some redundancy in breakdown situations. It also reduces the size of the subsequent loading problem. However, then the loading problem allocates operations to groups. This can limit the opportunities for better workload balance. Also, it may be that some operations are assigned to only one machine, as in the allocation of Tables 3 and 5.

An alternative to grouping machines in advance is to allocate operations to several machines, i.e., to perform partial pooling. This is now addressed in the machine loading problem, and is suggested for this particular FMS.

4.3 Machine Loading

Some problems with the allocation of operations to machines of Tables 3 and 5 are the following.

1. Workload per machine is not balanced.
2. Several operations are assigned to only one machine. This will cause a problem if that machine goes down.
3. If the production requirements change then the workloads shift. Balance can decrease and the allocations may become infeasible. Some machines may be allocated more work than what fits in a day.

Allocations of operations to machines can be found that attain a better balance (i.e., the best possible balance, if that is desired). The following formulation, Problem (P), provides one way of flexibly allocating operations. Notation is in Table 4.

$$\text{(P)} \qquad \min \sum_{k=1}^{11} \left(X_{Ak}+X_{Bk}\right)$$

subject to

$$\sum_{k=1}^{11} \left(X_{jk}\, tpo_j + X_{Ak} - X_{Bk}\right) \leq 1.1\, RW \tag{1}$$

$$\sum_{k} X_{jk} = 1, \qquad j = 1, \ldots, 11 \tag{2}$$

$$Y_{jk} \geq X_{jk}, \qquad \text{for all } j \text{ and } k \tag{3}$$

$$2 \leq \sum_{k=1}^{11} Y_{jk} \leq 3, \qquad j = 1, \ldots, 11 \tag{4}$$

$$\sum_{j=1}^{11} d_j \, Y_{jk} - \sum_{\substack{\forall \bar{B} \subset B_k \\ \text{such that } |\bar{B}|=2}} W_{\bar{B}} \left(\prod_{j \in \bar{B}} Y_{jk} \right) + \sum_{\substack{\forall \bar{B} \subset B_k \\ \text{such that } |\bar{B}|=3}} W_{\bar{B}} \left(\prod_{j \in B} Y_{jk} \right) \leq t_k \tag{5}$$

$$Y_{jk} = 0 \text{ or } 1$$

$$X_{jk}, X_{Ak}, X_{Bk} \geq 0$$

With the current set of part types to be machined, the two Rotoheads are never bottlenecks. The allocation here concerns the eleven MSRs. Problem (P) is a variation of the loading formulations of Stecke [1983, 1989] and Berrada and Stecke [1986].

The decision variables are the X_{jk} (the proportion of the total daily workload of operation j that is assigned to machine k) and the Y_{jk} (the counter for the number of times an operation has been assigned to the machines). The objective function minimizes the sum of the overloads and/or underloads on the machines.

Constraint (1) determines the proportion of the total daily workload required of each operation that is allocated to each machine. Here, RW is an input, having been calculated earlier. If perfect balance is desired, the 1.1 can be deleted. An overload or an underload is allowed in any case.

Constraint (2) ensures that all required work is allocated. Constraint (3) allows a count of the number of times that each operation is assigned to machines. Constraint (4) ensures that each operation is assigned to at least two machines (to provide a redundancy in the case of machine breakdowns), but to not more than three machines (there is usually no need for more allocations). This constraint can be changed easily if it becomes necessary or desirable to assign an operation to more or less machines. Constraint (5) considers tool magazine capacity. Tool duplication and tool overlap are considered for combinations of two and three operations. The constraint is easily extendable if larger combinations are to be considered. However, as we see in the Appendix, there is little overlap in tools for more operations. Also, with the current data, tool magazine capacity does not allow more than 3 operations per machine. The more general formulation remains here because new part types are likely to be added in the future. Finally, the Y variables are 0-1 and the X variables are continuous.

The fifth constraint is the only nonlinear constraint. Fortunately (from a mathematical point of view, not operationally), there is very little overlap in required cutters among operations. Indeed, the largest overlap is 4 slots for operations 1, 2, and 3, which together require 79 slots and so is infeasible. (See the tooling data in the Appendix.) The overlap is so small that it need not be considered. Then for our purpose, constraint (5) can at present be reduced to the following linear constraint:

$$\sum_{j=1}^{11} d_j Y_{jk} \leq t_k. \qquad (6)$$

As future part types or variants are added to the line, tool magazine capacity will be tighter and consideration of tool overlap will become more important. Also, operation and part redesign and part program redefinition may allow a larger overlap to occur in the current tool overlap of the operations. For these reasons, the more general formulation of constraint (5) is included and may be useful or necessary in the future.

The current formulation of Problem (P) is a (0-1) mixed integer program and can be solved quickly and easily using a standard integer programming package such as LINDO (Schrage [1981]). If the problem becomes nonlinear, it could be solved by linearizing the nonlinear terms with additional constraints and variables. More details on the actual solution of the loading problem are discussed in the Appendix, where the current tooling data is provided and analyzed.

4.4 Fixture Management

There are no fixture allocation problems. Since each fixture type is dedicated to a particular part type (for one to three mounts), there is no fixture sharing. The fixture problems here will be:

1. determining how many fixtures of each type should be in the system;
2. determining which fixture type (hence, part type) should be input into the system next.

Regarding the first problem, Table 2 provides the maximum number of fixtures of each type that will be available to the system. These maximum values were obtained by using a closed queueing network model based on mean value analysis. The analysis was done using the initial suggested operation allocation based on the average daily workloads of Table 3. This operation allocation did not balance workloads.

Balancing workloads tends to allow less in-process inventory. (See Shanthikumar and Stecke [1986].) Then by applying the 0-1 integer formulation of §4.3 to allocate operations to balance workloads, usually less than the maximum number of fixtures available should be required. Given the balanced allocation of operations to machines obtained by solving Problem (P), the closed queueing network model should be used to help specify an appropriate number of fixtures of each type to be on the system.

For the second fixture type problem, determining which fixture type should be input to the system next is related to determining which part type should be input next. This is now addressed in §4.5.

4.5 Scheduling

Scheduling could be tricky because of the nine fixture types required, the many mounts, the various numbers of parts per mount, and the multiple mounts per fixture. For example, the two cylinder heads each require five mounts on three fixtures types. See Table 3. The number of parts per mount per fixture may be 1, 2, 3, 4, or 5.

Because of the various sizes of the mounts, there will be small amounts of in-process inventory for almost all operations. Also, third mount parts for cylinder heads (part type 4) are finished in pairs, but wait until twelve parts are accumulated for AGV transport to a manual station for 196 minutes. Then the fourth mount operation finishes three parts at a time, to wait for twelve to accumulate for another visit to the manual station.

Despite these necessary coordinations, scheduling should not be difficult. After each machining operation, parts are washed and sometimes inspected. Most often, the pallet and fixture return to a particular L/UL station for remounting or exit from the FMS. Then the scheduling issue is largely just AGV traffic control. If there are several pallets/fixtures on different AGVs and waiting for a particular L/UL spot, we suggest the following priorities of service, with the highest priority specified first:

1. parts whose next visit is to a bottleneck machine;
2. parts whose next machine is free;
3. parts whose next operation is waiting for enough parts to accumulate for a visit to the manual station;
4. parts that are in-process, i.e., that are partially completed and have just been or need to be refixtured;
5. new parts waiting to be input into the system;
6. completed parts waiting to be unloaded.

Ties within each of these six categories of parts may be broken arbitrarily.

Current specifications are that the daily requirements should be about the same for a month at a time, with some variation from month to month. Then a periodic part input sequence may be appropriate, except when unexpected rush orders need to be accommodated.

Because of changing operation allocations, the bottleneck machine(s) may shift with time. Since processing times and requirements are known, the bottlenecks are likely to be identifiable.

The AGV moves have to be specified. However, operation times are long enough (all are between 16 and 51 minutes for the MSRs and all less than 15 minutes for the Rotohead indexers) that scheduling in real time and using priority rules should not pose problems.

4.6 Inventory Management

At present, the daily FMS production requirements will be generated from the monthly requirements. Then in general, the daily requirements throughout the month will be about the same. There may be some rush orders required or bad parts produced that need to be processed again. These would cause either slight or more major variations.

However, from month to month, both the total number of part types and the workload requirements can vary substantially, depending on the current market for cars and vans. Depending on which part types are ordered, the total processing requirements per operation can vary widely.

Indeed, in some months the FMS may be underutilized while in other months, the requirements could be more than the capacity during some days. Some inventory should be carried for the following reasons:

1. Unexpected machine breakdowns can reduce the system capacity significantly;
2. Daily workload variations need to be accommodated;
3. Rush orders may need to be added to the requirements;
4. Yield or scrap problems may occur.

Since workload will be allocated among the machines to approximately balance, there should be time at the end of each day to work ahead and build up some inventory to buffer future uncertainties, under normal operating conditions (no breakdowns, work stoppages, or other unforeseen idle time occurrences).

There are several ways to build up this inventory. One way is to produce parts whose next day's requirements can be met. This is the suggested inventory policy for another COMAU FMS in Torino, Italy. (See Stecke [1989].) A second alternative is to continue production as it has been, and to continue to produce all of the same parts that have been in production that day. This also takes advantage of the current tooling.

This second alternative for intelligent inventory buildup is recommended for this FMS for several reasons. Although it may seem to result in more in-process inventory at the end of the day, this is not a problem as this inventory accumulation is proportional to the following day's requirements. This latter approach is more appropriate for this FMS because for a month at a time, the daily requirements should be about the same.

If, under normal operating conditions, the FMS has enough capacity to meet the daily requirements and some to spare, inventory should be built up only to the following two days ahead. If there is further variability or some foreseeable loss of capacity (for example, due to necessary preventative maintenance), some further inventory should be accumulated. Also, as the end of the month nears and the new requirements become known, this information should also be considered. For example, if the daily workload is to increase, then additional inventory of the future requirements should be built up to cover the changeover.

The FMS does not need to and should not carry safety stock. Any inventory build-up will consist of actual requirements. The inventory policy can be termed JIC, i.e., building up inventory Just In Case (of machine breakdown and other uncertain undesirable events).

4.7 Implementation Issues

If the production requirements are fairly stable during a particular month, the algorithms and (0-1) integer program (P) of §4.3 need only to be run at the beginning of the month. If the requirements change, or part of the system is down, or new orders arrive, or there are scrap or yield problems, the algorithms should be run again to reallocate work. It should be sufficient to only run a *linear* version of Problem (P). This is discussed in the Appendix. The breakdown issues affecting such reallocation decisions are discussed subsequently in §5.

Other daily implementation functions include the following: checking to see if the necessary raw materials are available and ordering those that are not; and changing any worn or broken cutters.

5. BREAKDOWN CONSIDERATIONS

When the system is in full operation, there will usually be enough capacity to meet all requirements. An 85% system utilization is expected to be required from the FMS in order to meet requirements. However, when one or more machines are down for a period of time, there will likely not be enough capacity. The following precautions have been suggested here to help handle breakdown situations.

First, each operation will be assigned to two or three machines (when all machines are up). This will allow continued operation when a machine goes down, albeit at a reduced production rate. Second, spare time will be used at the end of a day to begin the following day's or two requirements. Such an inventory policy is also an insurance against unknown future undesirable breakdown effects.

Even though production will continue when a breakdown occurs, workload and/or cutters may need to be reassigned. First, an attempt should be made to estimate the length of time of a current breakdown as well as its effect on production. Then a linear programming version of Problem (P) can be run to only reallocate work (and not cutters) and balance workloads or just to feasibly meet the day's requirements, again without changing any cutters. If this cannot be done, then Problem (P) can be run to reallocate operations and to allow some cutters to be changed.

If there is not enough capacity to meet the day's requirements, the following steps need to be taken. First, some of the production may have to be sent to another department for job shop production. Other options include overtime production (elsewhere, not on the FMS) or subcontracting.

Pooling machines into identically tooled machine groups, as suggested by the initial allocation of Table 3, will also help in breakdown situations, especially if a machine in a pool goes down. Also, the information on the tool slot requirements for combinations of operations, as provided in Table A4 of the Appendix, can be used to allow manual reallocation decisions to be made.

In conclusion, the key operating problems are tool management or loading problems. Operations and their cutters need to be allocated among the eleven identical machine tools so as to allow the FMS to efficiently and effectively meet its daily production requirements and to adequately handle breakdown situations. The algorithms suggested here provide_a more flexible approach to operate the FMS successfully than the initially suggested fixed solution.

ACKNOWLEDGEMENTS

I'd like to thank the Referees for their helpful suggestions in improving the paper. Many thanks also to Gianni M. Secco-Suardo of COMAU for helpful discussions and support during the research development and also to Marzia Brunetto of COMAU for her help with the tool clustering in the Appendix. I also acknowledge a Summer Research Grant from the Business School of The University of Michigan.

BIBLIOGRAPHY

BERRADA, MOHAMMED and STECKE, KATHRYN E., "A Branch and Bound Approach for Machine Load Balancing in Flexible Manufacturing Systems", **Management Science**, Vol. 32, No. 10, pp. 1316-1335 (October 1986).

CAVAILLÉ JEAN-BERNARD and DUBOIS, DIDIER, "Heuristic Methods Based on Mean-Value Analysis for Flexible Manufacturing Systems Performance Evaluation", **Proceedings of the 21st IEEE Conference on Decision and Control**, Orlando, FL, pp. 1061-1065 (December 1982).

GRAY, ANN E., SEIDMANN, ABRAHAM, and STECKE, KATHRYN E., "Tool Management in Automated Manufacturing: Operational Issues and Decision Problems", Working Paper No. CMOM 88-03, William E. Simon Graduate School of Business, University of `Rochester, NY (November 1988).

MENGA, GIUSEPPE, BRUNO, G., CONTERNO, RENATO, and ACTIS DATO, M. "Modeling FMS by Closed Queueing Network Analysis Methods", **IEEE Transactions on Components, Hybrids, and Manufacturing**, CHM-7, No. 3, pp. 3-12 (September 1984).

REISER, M. and LAVENBERG, S. S., "Mean-Value Analysis of Closed Multichain Queueing Networks", **Journal of the Association for Computing Machinery**, Vol. 27, No. 2, pp. 313-322 (April 1980).

SCHRAGE, LINUS E., **Linear Programming Models with LINDO**, The Scientific Press, Palo Alto, CA (1981).

SHANTHIKUMAR, J. GEORGE and STECKE, KATHRYN E., "Reducing Work-in-process Inventory in Certain Classes of Flexible Manufacturing Systems", **European Journal of Operational Research**, Vol. 26, No. 2, pp. 266-271 (August 1986).

STECKE, KATHRYN E., "Formulation and Solution of Nonlinear Integer Production Planning Problems for Flexible Manufacturing Systems", **Management Science**, Vol. 29, No. 3, pp. 273-388 (March 1983).

STECKE, KATHRYN E., "Algorithms for Efficient Planning and Operation of a Particular FMS", **International Journal of Flexible Manufacturing Systems**, Vol. 1, No. 4, pp. 287-324 (September 1989).

SURI, RAJAN and HILDEBRANT, RICHARD R., "Modelling Flexible Manufacturing Systems Using Mean Value Analysis", **Journal of Manufacturing Systems**, Vol. 3, No. 1, pp. 27-38 (January 1984).

APPENDIX. TOOLING DATA AND ANALYSIS.

This Appendix contains the detailed tooling data for this FMS. The data is first presented, then manipulated and analyzed. The analysis of the particular data is necessary to support and sometimes simplify the algorithms presented in §4. In particular, the loading problem can be simplified, and this was the main problem to consider in the operation of this FMS. Consideration of the particular data allows the re-solution of the loading problem (sometimes necessary in breakdown situations) to often be merely a manual procedure using a table look-up.

Each of the eleven MSRs has one primary tool magazine that has 60 slots. All cutters take either one or three slots of magazine capacity. The tooling data is analyzed for the eleven operations identified in Table 2. This is in order to see the effects of tool magazine capacity restrictions and to identify potential pooling and partial pooling possibilities. If more pooling options can be identified, then the system can be operated more flexibly. Also, pooling and partial pooling automatically provide redundancy in tooling assignments for use in situations of random machine breakdowns.

Table A1 provides the basic tooling information, identifying (with a star) which cutters are required for each of the eleven operations. Most of the tools take one slot in a tool magazine. Those tools identified by the letter "T" cover three slots.

The main reason that the tooling data is compiled is to help the identification of the operations that use some of the same tools. Scanning lists of tools can begin to provide this information. Manipulating the tooling data can clarify the tool commonalities.

TABLE A1. Tooling Data for the FMS.

	OPERATIONS										
TOOLS	1	2	3	4	5	6	7	8	9	10	11
ADD01									*		
ADD02									*		
ADD03								*			
ADD04								*			
ADD05						*					
ADD06				*							
ADD07				*							

TABLE A1. Tooling Data for the FMS. (continued).

TOOLS	1	2	3	4	5	6	7	8	9	10	11
ADD08						*					
ADD09				*							
ALM01											*
ALM02											*
AMD01								*			
BAF01										*	
BAF02						*					
BAF03										*	
BAF04					*						
BAF05					*						
BAF06					*						
BAF07					*						
BAF08											*
BAS01							*				
BAF08											*
BAS01							*				
BAS02										*	
BAS03							*				
BAS04						*					
BAS05							*				
BAS06											*
BMA01										*	
BMA02										*	
BMA03										*	
BMA04										*	
BMA05										*	
BMA06						*					
BMA07						*					
BMA08						*					
BMA09						*					
BMA10						*					
BMA11									*		
BMA12									*		
FBS01							*				
FCO01								*			
FCO02								*			
FCO03							*			*	
FCO04									*		
FCO05				*							
FCO06	*										
FDB01		*				*					
FFI01	*	*	*								
FFI02	*	*	*						*		*
FFI03							*				
FFI04									*		*
FFI05						*					
FSG01								*			
FSG02				*							
FSG03								*			
LIS01			*								
LIS02									*		
LIS03	*		*								
LIS04	*										
LIS05						*					
LIS06	*										
LIS07			*								
LIS08						*					
LMD01	*										
LMD02		*	*								
LMD03						*					
LMD04						*					
LMD05					*						

TABLE A1. Tooling Data for the FMS. (continued).

TOOLS	1	2	3	4	5	6	7	8	9	10	11
MAS01			*								
MAS02	*	*	*				*	*			
MAS03		*	*		*		*				
MAS04							*		*		
MAS05	*										
MAS06			*								
MAS07	*		*								
MAS08							*		*		
MAS09			*				*				
MAS10						*					
PDD01			*								
PDD02									*		
PDD03			*								
PDD04							*	*			
PDD05	*	*	*								
PDD06			*								
PDD07			*								
PDD08							*				
PDD09							*				
PDD10	*										
TXX28								*			
TXX29								*			
PDD11								*			
PDD12						*					
PDD13			*								
PDD14	*										
PDD15	*										
PDD16			*								
PDD17							*	*			
PDD18			*				*				
PHS01							*				
PHS02				*							
PHS03		*									
PHS04									*		
PHS05									*		
PMD01	*										
PMD02	*										
PMD03			*								*
PMD04								*			
PMD05				*							
PMD06			*								
REG01											*
TXX01						*					
TXX02							*				
TXX03				*							
TXX04	*										
TXX05		*									
TXX06			*								
TXX07						*					
TXX08				*							
TXX09		*									
TXX10	*										
TXX11						*					
TXX12					*						
TXX13			*								
TXX14	*										
TXX15					*						
TXX16	*										
TXX17			*								
TXX18					*						
TXX19			*								
TXX20	*										

TABLE A1. Tooling Data for the FMS. (continued).

TOOLS	1	2	3	4	5	6	7	8	9	10	11
TXX21					*						
TXX22			*								
TXX23	*										
TXX24			*								
TXX25			*								
TXX26								*			
TXX27								*			
TXX28								*			
TXX29								*			
TXX30								*			
TXX31									*		
TXX32									*		
TXX33									*		
TXX34									*		
TXX35										*	
TXX36										*	

Tools common to two or more operations in Table A1 are next identified. Columns (operations) and then the rows (tools) of Table A1 are interchanged to position shared tooling together. The result is Table A2.

Table A2 provides the final clustering of common tools. With the current data, there is not much overlapping use of cutters. However, the data is incomplete at present. There may be additional benefits from observing common tooling in the future, as either the data changes or new part types are added to the FMS.

TABLE A2. Permuted Tooling Data Showing Common and Unique Tools.

	OPERATIONS										
TOOLS	1	2	3	5	7	8	9	11	6	10	4
FDB01		*							*		
FFI04							*	*			
PDD04					*	*					
PDD17					*	*					
MAS04											
MAS08					*		*				
FCO03					*					*	
LIS03	*		*								
MAS07	*		*								
FFI01	*	*	*								
PDD05	*	*	*								
MAS02	*	*	*		*	*					
FFI02	*	*	*				*	*			
LMD02		*	*								
MAS03		*	*	*	*						
MAS09			*		*						
PDD18			*		*						
PMD03			*					*			
FCO06	*										

TABLE A2. Permuted Tooling Data Showing Common and Unique Tools.

TOOLS	1	2	3	5	7	8	9	11	6	10	4
LIS04	*										
LIS06	*										
LMD01	*										
MAS05	*										
PDD10	*										
PDD14	*										
PDD15	*										
PMD01	*										
PMD02	*										
TXX04	*										
TXX10	*										
TXX14	*										
TXX16	*										
TXX20	*										
TXX23	*										
PHS03		*									
TXX05		*									
TXX09		*									
LIS01			*								
LIS07			*								
MAS01			*								
MAS06			*								
PDD01			*								
PDD03			*								
PDD06			*								
PDD07			*								
PDD13			*								
PDD16			*								
PMD06			*								
TXX06			*								
TXX13			*								
TXX17			*								
TXX19			*								
TXX22			*								
TXX24			*								
BAF04				*							
BAF05				*							
BAF06				*							
BAF07				*							
LMD05				*							
TXX12				*							
TXX15				*							
TXX18				*							
TXX21				*							
BAS01					*						
BAS03					*						
BAS05					*						
FBS01					*						
FFI03					*						
PDD08					*						
PDD09					*						
PHS01					*						
TXX02					*						
ADD03						*					
ADD04						*					
AMD01						*					
FCO01						*					
FCO02						*					
FSG01						*					
FSG03						*					
PDD11						*					
PMD04						*					
TXX26						*					

TABLE A2. Permuted Tooling Data Showing Common and Unique Tools.

TOOLS	1	2	3	5	7	8	9	11	6	10	4
TXX27						*					
TXX28						*					
TXX29						*					
TXX30						*					
ADD01							*				
ADD02							*				
BMA11							*				
BMA12							*				
FCO04							*				
LIS02							*				
PDD02							*				
PHS04							*				
PHS05							*				
TXX31							*				
TXX32							*				
TXX33							*				
TXX34							*				
ALM01								*			
ALM02								*			
BAF08								*			
BAS06								*			
REG01								*			
TXX35								*			
ADD05									*		
ADD08									*		
BAF02									*		
BAS04									*		
BMA06									*		
BMA07									*		
BMA08									*		
BMA09									*		
BMA10									*		
FFI05									*		
LIS05									*		
LIS08									*		
LMD03									*		
LMD04									*		
MAS10									*		
PDD12									*		
TXX01									*		
TXX07									*		
TXX11									*		
BAF01										*	
BAF03										*	
BAS02										*	
BMA01										*	
BMA02										*	
BMA03										*	
BMA04										*	
BMA05										*	
ADD06											*
ADD07											*
ADD09											*
FCO05											*
FSG02											*
PHS02											*
PMD05											*
TXX03											*
TXX08											*

Table A3 provides information on the number of tools and the number of magazine slots for each operation. The data may be incomplete at present. Tables A2 and A3 can be updated as additional information is obtained about either the current or future part types.

The final two tables (A3 and A4) provide all of the information that would be useful to the FMS manager when she or he needs to make some minor operation allocation or tooling changes. Such changes may be necessary if there is a rush order or a disturbance such as a machine breakdown. These two tables allow a manual re-solution of the system loading problem.

To summarize the information required for the algorithms of §4, Table A3 provides the data on tool slots. Table 3 contains the processing times required for each operation. The additional information in Table A3 on the number of *tools* required for each operation is not necessary for our purposes here. It would be useful for a future simulation study, which could model, for example, the time required to change tools. Also, the information on the number of tools will be needed during system operation.

TABLE A3. Tool Slots and Tools Required Per Operation.

OPERATION	1	2	3	4	5	6	7	8	9	10	11
TOOL SLOTS	**34**	**14**	**43**	**13**	**18**	**26**	**20**	**27**	**25**	**9**	**14**
TOOLS	22	10	29	9	10	20	18	17	17	9	10

With the current tool information, the total number of tools (and tool slots) required by all eleven operations is 143 (and 215). This counts each tool only once, even if it is used for several operations. Also, no allowance for sister tooling (duplicate tooling within a magazine) is yet made.

A listing of the tooling requirements for each of all combinations of operations was compiled. For this FMS, there is little overlap of cutters required for groups of operations. For another FMS analyzed in Stecke [1989], the results are quite different. A significant tool overlap could be taken advantage of in that system.

There is a large computer output (called *all combinations*) that provides, for each of all possible combinations of operations that may be allocated together to the same machine, the following information:

- * the *total number* of cutting tools required and tool slots occupied by the particular *combination*;
- * the number of *unique tools* and *tool slots* required *only* by each component of the particular combination;
- * the number of *tools in common* required by *all* of the components of the particular combination.

Scanning the 63 pages of *all combinations* of operations assigned to the same machine, we can see the following. There are eleven combinations of the eleven operations grouped in sets of size 10 $\left[\binom{11}{10} = 11\right]$. Each of these eleven combinations would require from 183-208 slots in a tool magazine, depending on the combination. Then *all* of these combinations are infeasible, in terms of the tools fitting into one machine's magazine.

There are 55 combinations of the eleven operations grouped in sets of size 9 $\left[\binom{11}{9} = 55\right]$. Each of these 55 combinations would require from 153-200 slots in a tool magazine, depending on the particular combination. *All* of these combinations are infeasible also.

There 165 combinations of the eleven operations grouped in sets of size 8 $\left[\binom{11}{8} = 165\right]$. Each of these 165 combinations require from 128-187 slots in a tool magazine. Then these combinations could never be assigned together to the same machine.

All 330 combinations of 7 operations assigned to the same machine take between 104 and 177 spaces in a magazine. All 462 combinations of 6 operations take between 87 and 164 slots. All 462 combinations of 5 operations take between 66 and 147 slots. Then all of these combinations too are infeasible.

All 330 combinations of 4 operations take between 49 and 123 slots. However, only 13 of the 330 combinations can fit within the 60 slot capacity. Hence we can eliminate these combinations from consideration.

There are many combinations of two and three operations that require less than 60 slots and can be assigned to the same machine. Allowing these possibilities:

1. automatically provides redundancies to handle random breakdowns;
2. allows a better workload balance to be obtained.

Table A4 contains information on tool slot requirements for many feasible (and also infeasible) combinations of the eleven operations assigned to the same machine. The original 63 pages of information is reduced to the following four pages of Table A4 by deleting the combinations noted above that could never be assigned to the same machine.

The first two or three columns of Table A4 list the two or three operations in a particular *combination*. The next column (labeled TOOL SLOTS) provides the number of tool slots taken in a magazine by the combination. The next two or three columns give the numbers of slots taken by unique tools specific to each operation in the combination. The final column provides the number of tool slots taken by tools that are *common* to all of the operations in the combination.

TABLE A4. Total Tool Space, Unique Tools, and Common Tools for Some Feasible Combinations of Two and Three Operations.

COMBINATION		TOOL SLOTS	SPACE THAT THE FIRST OPN TAKES	SPACE THAT THE SECOND OPN TAKES	SPACE THAT THE THIRD OPN TAKES	OVERLAP
1	2	**44**	30	10		4
1	3	71	28	37		6
1	4	**47**	34	13		0
1	5	**52**	34	18		0
1	6	**60**	34	26		0
1	7	**53**	33	19		1
1	8	**60**	33	26		1
1	9	**58**	33	24		1
1	10	**43**	34	9		0
1	11	**47**	33	13		1
2	3	**51**	8	37		6
2	4	**27**	14	13		0
2	5	**31**	13	17		1
2	6	**39**	13	25		1
2	7	**32**	12	18		2
2	8	**40**	13	26		1
2	9	**38**	13	24		1
2	10	**23**	14	9		0
2	11	**27**	13	13		1
3	4	**56**	43	13		0
3	5	**60**	42	17		1
3	6	69	43	26		0
3	7	**59**	39	16		4
3	8	69	42	26		1
3	9	67	42	24		1
3	10	**52**	43	9		0
3	11	**55**	41	12		2
4	5	**31**	13	18		0

TABLE A4. Total Tool Space, Unique Tools, and Common Tools for Some Feasible Combinations of Two and Three Operations.

COMBINATION			TOOL SLOTS	SPACE THAT THE FIRST OPN TAKES	SPACE THAT THE SECOND OPN TAKES	SPACE THAT THE THIRD OPN TAKES	OVERLAP
4	6		39	13	26		0
4	7		33	13	20		0
4	8		40	13	27		0
4	9		38	13	25		0
4	10		22	13	9		0
4	11		27	13	14		0
5	6		44	18	26		0
5	7		37	17	19		1
5	8		45	18	27		0
5	9		43	18	25		0
5	10		27	18	9		0
5	11		32	18	14		0
6	7		46	26	20		0
6	8		53	26	27		0
6	9		51	26	25		0
6	10		35	26	9		0
6	11		40	26	14		0
7	8		44	17	24		3
7	9		43	18	23		2
7	10		28	19	8		1
7	11		34	20	14		0
8	9		52	27	25		0
8	10		36	27	9		0
8	11		41	27	14		0
9	10		34	25	9		0
9	11		37	23	12		2
10	11		23	9	14		0
1	2	3	79	28	8	35	4
1	2	4	57	30	10	13	0
1	2	5	61	30	9	17	0
1	2	6	69	30	9	25	0
1	2	7	62	30	9	18	1
1	2	8	70	30	10	26	1
1	2	9	68	30	10	24	1
1	2	10	53	30	10	9	0
1	2	11	57	30	10	13	1
1	3	4	84	28	37	13	0
1	3	5	88	28	36	17	0
1	3	6	97	28	37	26	0
1	3	7	87	28	34	16	1
1	3	8	97	28	37	26	1
1	3	9	95	28	37	24	1
1	3	10	80	28	37	9	0
1	3	11	83	28	36	12	1
1	4	5	65	34	13	18	0
1	4	6	73	34	13	26	0
1	4	7	66	33	13	19	0
1	4	8	73	33	13	26	0
1	4	9	71	33	13	24	0
1	4	10	56	34	13	9	0
1	4	11	60	33	13	13	0
1	5	6	78	34	18	26	0
1	5	7	70	33	17	18	0
1	5	8	78	33	18	26	0
1	5	9	76	33	18	24	0
1	5	10	61	34	18	9	0
1	5	11	65	33	18	13	0
1	6	7	79	33	26	19	0
1	6	8	86	33	26	26	0
1	6	9	84	33	26	24	0

TABLE A4. Total Tool Space, Unique Tools, and Common Tools for Some Feasible Combinations of Two and Three Operations.

COMBINATION			TOOL SLOTS	SPACE THAT THE FIRST OPN TAKES	SPACE THAT THE SECOND OPN TAKES	SPACE THAT THE THIRD OPN TAKES	OVERLAP
1	6	10	69	34	26	9	0
1	6	11	73	33	26	13	0
1	7	8	77	33	17	24	1
1	7	9	75	32	17	22	0
1	7	10	61	33	18	8	0
1	7	11	66	32	19	13	0
1	8	9	84	32	26	24	0
1	8	10	69	33	26	9	0
1	8	11	73	32	26	13	0
1	9	10	67	33	24	9	0
1	9	11	70	33	23	12	1
1	10	11	**56**	33	9	13	0
2	3	4	64	8	37	13	0
2	3	5	68	8	37	17	1
2	3	6	76	7	37	25	0
2	3	7	67	8	35	16	2
2	3	8	77	8	37	26	1
2	3	9	75	8	37	24	1
2	3	10	**60**	8	37	9	0
2	3	11	63	8	36	12	1
2	4	5	**44**	13	13	17	0
2	4	6	**52**	13	13	25	0
2	4	7	**45**	12	13	18	0
2	4	8	**53**	13	13	26	0
2	4	9	**51**	13	13	24	0
2	4	10	**36**	14	13	9	0
2	4	11	**40**	13	13	13	0
2	5	6	**56**	12	17	25	0
2	5	7	**49**	12	17	18	1
2	5	8	**57**	12	17	26	0
2	5	9	**55**	12	17	24	0
2	5	10	**40**	13	17	9	0
2	5	11	**44**	12	17	13	0
2	6	7	**57**	11	25	18	0
2	6	8	65	12	25	26	0
2	6	9	63	12	25	24	0
2	6	8	65	12	25	26	0
2	6	9	63	12	25	24	0
2	6	10	**48**	13	25	9	0
2	6	11	**52**	12	25	13	0
2	7	8	**52**	12	25	13	0
2	7	9	**54**	11	16	22	0
2	7	10	**40**	12	17	8	0
2	7	11	**45**	11	18	13	0
2	8	9	64	12	26	24	0
2	8	10	**49**	13	26	9	0
2	8	11	**53**	12	26	13	0
2	9	10	**47**	13	24	9	0
2	9	11	**50**	13	23	12	1
2	10	11	**36**	13	9	13	0
3	4	5	73	42	13	17	0
3	4	6	82	43	13	26	0
3	4	7	72	39	13	16	0
3	4	8	82	42	13	26	0
3	4	9	80	42	13	24	0
3	4	10	65	43	13	9	0
3	4	11	68	41	13	12	0
3	5	6	86	42	17	26	0
3	5	7	76	39	17	16	1

TABLE A4. Total Tool Space, Unique Tools, and Common Tools for Some Feasible Combinations of Two and Three Operations.

COMBINATION			TOOL SLOTS	SPACE THAT THE FIRST OPN TAKES	SPACE THAT THE SECOND OPN TAKES	SPACE THAT THE THIRD OPN TAKES	OVERLAP
3	5	9	84	41	17	24	0
3	5	10	69	42	17	9	0
3	5	11	72	40	17	12	0
3	6	7	85	39	26	16	0
3	6	8	95	42	26	26	0
3	6	9	93	42	26	24	0
3	6	10	78	43	26	9	0
3	6	11	81	41	26	12	0
3	7	8	83	39	14	24	1
3	7	9	81	38	14	22	0
3	7	10	67	39	15	8	0
3	7	11	71	37	16	12	0
3	8	9	93	41	26	24	0
3	8	10	78	42	26	9	0
3	8	11	81	40	26	12	0
3	9	10	76	42	24	9	0
3	9	11	78	41	23	11	1
3	10	11	64	41	9	12	0
4	5	6	**57**	13	18	26	0
4	5	7	**50**	13	17	19	0
4	5	8	**58**	13	18	27	0
4	5	9	**56**	13	18	25	0
4	5	10	**40**	13	18	9	0
4	5	11	**45**	13	18	14	0
4	6	7	**59**	13	126	20	0
4	6	8	66	13	26	27	0
4	6	9	64	13	26	24	0
4	6	10	**48**	13	26	9	0
4	6	11	**53**	13	26	14	0
4	7	8	**57**	13	17	24	0
4	7	9	**56**	13	18	23	0
4	7	10	**41**	13	19	8	0
4	7	11	**47**	13	20	14	0
4	8	9	65	13	27	25	0
4	8	10	**49**	13	27	9	0
4	8	11	**54**	13	27	14	0
4	9	10	**47**	13	25	9	0
4	9	11	**50**	13	23	12	0
4	10	11	**36**	131	9	14	0
5	6	7	63	17	26	19	0
5	6	8	71	18	26	27	0
5	6	9	69	18	26	25	0
5	6	10	**53**	18	26	9	0
5	6	11	**58**	18	26	14	0
5	7	8	61	17	16	24	0
5	7	9	60	17	17	23	0
5	7	10	**45**	17	18	8	0
5	7	11	**51**	17	19	14	0
5	8	9	70	18	27	25	0
5	8	10	**54**	18	27	9	0
5	8	11	**59**	18	27	14	0
5	9	10	**52**	18	25	9	0
5	9	11	**55**	18	23	12	0
5	10	11	**41**	18	9	14	0
6	7	8	70	26	17	24	0
6	7	9	69	26	18	23	0
6	7	10	**54**	26	19	8	0
6	7	11	**60**	26	20	14	0
6	8	9	78	26	27	25	0
6	8	10	62	26	27	9	0

TABLE A4. Total Tool Space, Unique Tools, and Common Tools for Some Feasible Combinations of Two and Three Operations.

COMBINATION			TOOL SLOTS	SPACE THAT THE FIRST OPN TAKES	SPACE THAT THE SECOND OPN TAKES	SPACE THAT THE THIRD OPN TAKES	OVERLAP
6	8	11	67	26	27	14	0
6	9	10	**60**	26	25	9	0
6	9	11	63	26	23	12	0
6	10	11	**49**	26	9	14	0
7	8	9	67	15	24	23	0
7	8	10	**52**	16	24	8	0
7	8	11	**58**	17	24	14	0
7	9	10	**51**	17	23	8	0
7	9	11	**55**	18	21	12	0
7	10	11	**42**	19	8	14	0
8	9	10	61	27	25	9	0
8	9	11	64	27	23	12	0
8	10	11	**50**	27	9	14	0
9	10	11	**46**	23	9	12	0

Note that some of the combinations of Table A4 are infeasible. These are included in the Table so that one can see at a glance which combinations are or are not allowed. The feasible combinations are noted in **boldface**. Another, smaller Table consisting of only the feasible combinations could be extracted from Table A4.

For easy look up, Table A4 contains a complete and concise set of tool occupation and tool duplication information that is required for the algorithms of §4. The information on common and unique tooling and tool slot requirements is useful for determining the maximum amount of potential pooling and partial pooling. Table A4 also displays the consequences, in terms of tool magazine capacity, of allocating various combinations of operations to machines.

The maximum number of tool slots required for any of the combinations in Table A4 is 97 slots. This indicates that about a magazine and a half is sufficient to contain the tools required for all combinations of two and three operations. This has interesting implications for both pooling and partial pooling potential. Any combination of *any* two or three operations can be duplicated twice by using only three machines.

The data may not be complete. Additional tools may be required to process the operations. New part types may be machined on the FMS in the future. As further information is obtained or new part types introduced into the FMS, these Tables can be updated. If more tools are required, the tool magazine capacity will be tighter, and less pooling and partial pooling may be possible. This is one reason why the formulations of §4 need to be provided in a general form.

In addition, some tools may be used often enough that several copies of each may need to be loaded in the magazines. Cutting time requirements for these tools may be high. There is no information to date on the amount of such sister tooling required. This information could reduce the amount of partial pooling that could be done, since more space in the magazines would be required for the sisters. Since cutting time/cutter is often small for aluminum parts, placement in the magazine may sometimes also be important.

When there are new orders or breakdowns, there may be either capacity problems or workload balance problems. If machines are pooled, shifting workload is easy and is a linear program. If this is not enough to solve the loading problem, some operations (and hence some tools) may have to be shifted from one machine to another. The information in Table A4 and the total processing time requirements of each operation are all that is needed to help make such reallocation decisions. These decisions can often be made manually. If some workload has to be shifted, for various potential reallocations to machines, Table A4 contains: the total number of tool slots required; the number of *new* tool slots required; and for use in formulation (P), the tool overlap as any new tools are included in the same magazine with the current tools.

To summarize, Table A4 is useful if tools or operations need to be reallocated in the case of machine breakdowns or new orders or whatever. A linear program can be run to reallocate workload to balance and Table A4 (or the smaller version) then consulted to check tool magazine capacity feasibility.