OPTIMISATION OF WORK FLOW

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AeroSpace Technologies of Australia (ASTA) is a supplier of aircraft components for several of the world's major aircraft manufacturers. Its anticipation of a substantial increase in demand has led to concern as to its ability to satisfy customer imposed schedules. ASTA's main concern is scheduling at its five autoclaves. The autoclaves, which are large pressurised ovens in which components are cured before non-destructive testing and final assembly, appear to be the bottlenecks in ASTA's manufacturing process. ASTA came to the Australian Mathematics-in-Industry Study Group (MISG) with the objective of developing an optimised loading plan for the autoclaves to improve their utilisation while meeting demand for final components. This report discusses the results of an intensive three day study by the MISG group working on the ASTA problem. Its findings were that:

- Modifying the way in which Materials Requirements Planning (MRP) is used may usefully increase autoclave utilisation.
- A single product which will account for 60% of factory hours could and should be scheduled separately.
- It is feasible and very helpful to group products into a small number of sets with common autoclave processing requirements.
- Integer programming models modelling the production line show considerable promise and should be developed further.

Members of MISG are continuing work with ASTA on this problem.

1. Introduction

AeroSpace Technologies of Australia (ASTA) is a world class supplier to the three major aircraft manufacturers; Aerospatiale, Boeing, and McDonnell Douglas. At present, ASTA makes metal floor support structures and landing gear doors for Aerospatiale; rudders, flaps, and slat wedges for Boeing; and trailing edge flaps for McDonnell Douglas.

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ASTA's manufacturing processes comprise airframe assembly, metal forming and fabrication, and structural bonding. The company employs 500 people at its Fishermens Bend plant, and it designs as well as manufactures aircraft components.

The Structural Bonding Centre (SBC) is one of ASTA's key facilities and integrates a wide range of capabilities needed to manufacture large composite sub-components to the aerospace industry's exacting standards. The SBC's activities include material storage and preparation, composite lay-up, honeycomb profiling, adhesive primer application, metal bonding, curing, and comprehensive non-destructive testing.

The commercial aerospace industry is in an economic growth period, and ASTA expects an increase in their existing programs' volumes and to be involved in new programs. Consequently ASTA wants to improve utilization of production capacity at their existing facilities. It was with this broad objective in mind that ASTA approached the MISG.

2. Problem description

ASTA's SBC makes composite non-metallic panels and cures metal to metal bonded aircraft parts. Its manufacturing process is a sequential process except that the line is interrupted by a batch process — curing the parts in an autoclave. The processes involve sophisticated technology and materials, small tolerances and high levels of cleanliness. At present the SBC work eighteen 8-hour shifts per week. Three extra shifts can be used to recover from rework or machine down time.

2.1 The autoclaves

An autoclave is an oven in which parts can be 'cooked' or cured at prescribed temperatures and pressures. The customer prescribes each part's cure cycle. Typically, a cycle will prescribe a rate of temperature and pressure increase, a maximum temperature and pressure, the time for which these must be maintained, and the rate at which temperature and pressure must fall to room temperature and pressure. Fortunately, each customer tends to prescribe the same cycle for many of the parts comprising a final product. Parts, e.g. parts of a rudder, are usually vacuum-packed before being cured.

ASTA has five autoclaves, comprising the autoclave cell, which vary markedly in size (some big components are too big for the small autoclaves) and the temperatures and pressures they can reach.

2.2 Problem characteristics

The SBC's scheduling problem has the following particular features:

- Orders for components are usually regular and known months in advance.
- The company feels that the autoclave cell is the bottleneck in SBC affecting capability to deliver panels to Assembly for final component build up.
- A possible constraint is the limited number of *tools* and *trolleys*. A tool is a mandrel on which a part is laid up. Trolleys are used to move tools to the autoclaves for curing, so that they may be wheeled into an autoclave. Although there are a few parts which can use a common tool, most have a unique tool. For most parts there is one, occasionally two tools — this is a factor of production rate. A part occupies its tool from when laying up starts until it has been cured. After curing, it is often convenient, but not necessary, to leave the part on its tool. The part is removed from the tool for Non-Destructive Testing (NDT) and trimming then across to the Airframe Assembly Centre (AAC) for assembly. When the part has been removed from its tool the tool becomes available for laying up another part.

  A part will usually occupy a tool for two or three days. If that part type has only one tool then only one such part can be made in every two or three days. Tools are expensive and occupy appreciable floor space, so the company is reluctant to buy more.
- Floor space is another possible constraint particularly influencing the option of levelling production by completing production in advance of delivery date. One final product, a rudder, is 11 metres long; its tool is bigger.
- ASTA currently use a Manufacturing Resource Planning (MRP II) system (MAN-FACT II). It is highly likely that future implementations would have to be built around this system.

3. ASTA's objectives

The Structural Bonding Centre management believe that their five autoclaves comprise a bottleneck in their operations and have noted that scheduling difficulties result in the autoclaves being run at less than 50% of their full capacity on average (it was hard to determine the precise figure).

In the short term, ASTA want to find a better way of scheduling autoclave use. The cost of running an autoclave cycle is (i) hard to establish and (ii) substantially independent on how full the autoclave is. On the face of it, the company could save money by running an autoclave 80% full instead of running it twice only 40% full. It was noted at the MISG that, in many other cases, high utilisation almost always implies long queues and high work in progress (WIP) costs (Karmarkar, 1987). In ASTA's case, because the demand is regular and known well in advance, this might not follow.

In the long term, ASTA wanted a means to schedule SBC processes and optimise work flow through the Centre.

3.1 Current scheduling practice

Operations within the SBC are recognised by ASTA as the most critical factor in efficiency improvement. A typical sequence of production processes within this centre includes:

1. Removal of raw material from the freezer. Raw materials eventually deteriorate if not kept in the freezer, but they may be safely left at room temperature for at least a month.
2. Plies are cut using a Gerber machine.
3. Plies are packed in a kit and the kit is refrozen.
4. When required, the kit is removed and layed-up on tools; to lay up means to build up a part such as a rudder from kits; build up means gluing layers of lifed material to construct the panel.
5. When lay-up is complete the part is vacuum bagged.
6. Bagged parts are cured in an autoclave.
7. Parts are unbagged and trimmed and drilled as required.
8. Non-destructive testing is carried out.

It is the wide range of products requiring a diversity of raw materials having different storage lives, manufacturing processes, and cure times which creates a complex network of trade-offs which the SBC manager must deal with.

3.2 Problems associated with current scheduling practice

Current scheduling practice, incorporating the company's planning (MRP II) system, is such that the lay-up of carbon fibre plies, a labour intense activity, drives the autoclave cure cycles. Intuitively, ASTA believes that cure cycles are bottlenecks which drive all other processes in the SBC.

In simple terms, MRP notes when final assemblies are required to be shipped from AAC and works back through all production processes, using lead and process times to determine when the jobs should be initiated in all three manufacturing centres of ASTA. ASTA currently organises work so that all the parts comprising a component e.g. composite panels and machined hinges, arrive at the *assembly area* at the same time with sufficient lead time to support the customers' requirements.

As the SBC parts comprising one final component tend to have the same curing requirements, it is possible to cure most of them simultaneously in one autoclave. The MRP system as presently used, oriented to the assembly centre's requirements, tends to schedule these parts for processing at the autoclaves at different times. This makes it difficult to fill an autoclave with parts that have a common cure cycle.

3.3 Project aims and objectives

The challenge that ASTA presented to the MISG group was to optimise the flow of work through the SBC to incorporate:

- loading at all SBC processes
- shop scheduling
- life material purchase.

As a consequence their objectives were to develop

- an optimised loading plan for the five autoclaves, and
- the process flow back for up-stream activities.

3.4 MISG discussion

Initial discussion at the MISG centred around developing a suitable method for finding sets of parts (referred to as *logical sets*, see Section 4.1) which could be autoclaved together so that better utilization of the autoclaves could be achieved. It was subsequently pointed out that a better objective was to minimise WIP since the cost of WIP is several orders of magnitude higher than the monthly running cost of an autoclave. However the focus of discussion soon turned to the consequences of batch scheduling at autoclaves and its effect on up-stream activity. Indeed any attempt to reorganise scheduling at the autoclaves must be based on the assumption that members of a logical set of components would arrive at the front of the autoclaves within a short time of each other. However it soon became apparent that the MRP system, as it was currently configured, would not release parts to allow this to happen. One could not then look at the autoclave scheduling problem in isolation from the MRP release schedule. A revised objective in relation to the autoclaves was then proposed, namely: Optimise loading at the autoclaves, taking into account:

- MRP release of products up-stream
- product characteristics, namely: cure cycle times, project numbers, and physical size
- due dates for final components.

Much of the group's attention was then concentrated on identifying relevant data and techniques for achieving these objectives.

The MISG group also noted that orders for an individual product would, from mid 1997, be regular and absorb about 60% of SBC's total production hours. It was therefore suggested that the group examine the possibility of finding a simple production schedule for these panels. That would allow this part, and the resources which it used, to be subtracted thereby reducing the problem complexity.

A fundamental question was to identify the relevant decision variables. How would the SBC implement any of the group's recommendation? One such decision appeared to be whether or not to use the company's MRP II system differently. Another, day to day set of decisions arises when an autoclave has been emptied. With what parts should it next be loaded? Should it be run partially full or should starting a cycle be deferred until other compatible parts arrive?

It became apparent that the problem could be dealt with in different ways. Four clearly defined tasks became apparent and a detailed account of each of these, and the extent to which it contributed to the objectives will be given in Section 4.

3.5 Past work

The problem under consideration has some generic features which have been identified in the literature as a combination of discrete and batch processing (Ahmadi *et al.*, 1992; Bhatnagar *et al.*, 1997).

Much of the reported work has been in relation to the electronics industry with the manufacturing of printed circuit boards (PCB's), where after a sequence of discrete processes, the PCB's are 'burnt in' in the final stage in a batch process. The autoclave can 'burn in' many boards simultaneously. Most of the earlier work in this area concentrates on modelling the batch processes only, while the more recent papers, notably by Bhatnagar *et al.*, have recognised that the upstream discrete scheduling activities cannot be overlooked. While the features of the ASTA problem are distinctly different from those reported in the literature, it is interesting to note that IP models have been implemented in several instances.

It is worth noting a comment by Bhatnagar *et al.* regarding the practice of running high capacity batch processes at high utilization. It has been shown that the perverse effect of this practice is to increase the WIP (Karmarkar, 1987). Since the ASTA problem has similar characteristics and potential, we believe that careful attention should be paid to this phenomenon when determining appropriate objectives.

4. Problem segmentation

The outcomes from the four groups formed at the MISG will now be detailed.

4.1 Logical sets

There are three compelling reasons for grouping certain sets of components when considering the ASTA scheduling problem. First, the large number of components when scheduled individually would give rise to a problem of enormous computational complexity. Second, it is logical to group certain components by virtue of common properties, particularly in relation to the autoclaves. Third, ASTA was already scheduling their autoclaves on an *ad hoc* basis using grouped sets of components. Consequently, we have constructed *logical sets* as the units on which to base scheduling strategies.

Logical sets are sets of components that can be cured together. Membership of logical sets is determined by reference to:

1. cure cycle number
2. cure time
3. project number
4. cure cycle stage and
5. autoclave compatibility.

The packing problem

It is desirable that a scheduling system not only delivers parts of the same logical set to the autoclave cell simultaneously, but delivers a quantity which nearly fills an autoclave. Thus we also associate with each logical set a quantity, so that each logical set comprises a number of parts with the same cure cycle which fill, or nearly fill, an autoclave. Enumeration has shown that there were only about 30 such logical sets.

Figure 1 shows details of the 30 logical sets determined on this basis. A further four logical sets can be defined in relation to oven use, but are not considered here since the oven is not a bottleneck. The first nine entries in the table clearly show how logical sets are distinguished according to cure cycle number, hours, and project number. Entries ten and eleven, for example, illustrate that each of a number of multiple cure cycles is identified as a distinct logical set for scheduling purposes. Note that in some cases e.g. sets 27, 28, and 29, cure cycles and trolley conditions change for each distinct stage. Figure 1 also shows autoclave/trolley capacities, as well as the first choice selection of trolleys for autoclaves, based on maximising the autoclave capacity.

4.2 Integer programming models

This section concentrates on modelling the batch processes at the autoclaves. It is assumed that up-stream scheduling is enabled via the MRP system, in such a way that the logical sets of components arrive at the autoclaves as required by these models. This will be discussed in greater detail in Section 4.4.

Autoclave / Trolley Capacities

AC	Trolley	Area (Sqm)
1	#1 #3	8.4 21.4
2	#1 #2 #2A #3	8.4 35.9 32.1 21.4
3	#1 #2A #3	8.4 32.1 21.4
4	#4	5.3
5	#2A #3 #5	32.1 21.4 44.3

Logical Group	Project Number	Cure Number	Cure Duration	Compatible Trolleys	Compatible Autoclaves	Area (Sqm)	No. Trolleys or Shifts AC-1	AC-2	AC-3	AC-4	AC-5	Qty (Jan)
1	A	A-001	3.5	#1, #3 OR #4	1, 2 OR 4	13.2	1	1		4		4
2	A	A-002	5.4	#1, #2 OR #3	1, 2 OR 3	8.0	1	1	1			4
3	B	B-001	5.2	#2 OR #4	2 OR 4	1.4		1		1		4
4	B	B-002	6.5	#5	5	104.0					3	4
5	C	C-002	5.5	#5	2 OR 5	5.7		1			1	11
6	C	C-002	6.5	#5	2 OR 5	38.7		2			2	11
7	D	D-001	5.2	#2 OR #4	2 OR 4	18.6		1		5		5
8	D	D-002	6.5	#5	5	167.4					5	5
9	E	E-001	12.0	#2	2	45.2		2				3
10	E	E-002 (1st)	5.2	#1	1	13.8	3					3
11	E	E-002 (2nd)	5.5	#1	1	13.8	3					3
12	F	F-001	4.2	#1, #2 OR #3	1, 2 OR 3	18.0	2	1	2			1
13	F	F-002 (1st)	5.0	#1, #2 OR #3	1, 2 OR 3	10.5	1	1	1			1
14	F	F-002 (2nd)	5.0	#1, #2 OR #3	1, 2 OR 3	10.5	1	1	1			1
15	F	F-002 (3rd)	5.0	#1, #2 OR #3	1, 2 OR 3	10.5	1	1	1			1
16	G	G-001 (1st)	4.0	#1, #2 OR #3	1, 2 OR 3	1.5	1	1	1			1
17	G	G-001 (2nd)	4.0	#1, #2 OR #3	1, 2 OR 3	1.5	1	1	1			1
18	H	H-001	6.5	#2	2, 3 OR 5	56.6		2	2		2	5
19	H	H-002 (1st)	8.0	N/A	2 OR 3	12.6		1	1			5
20	H	H-002 (2nd)	8.0	N/A	2 OR 3	13.1		1	1			5
21	H	H-002 (3rd)	3.0	N/A	3	13.1			1			5
22	H	H-003 (1st)	6.0	#1	2	37.8		2				5
23	H	H-003 (2nd)	6.0	#1	2	12.6		1				5
24	H	H-003 (3rd)	6.0	#1	2	12.6		1				5
25	I	I-001	8.5	#1 OR #3	1 OR 3	8.6	1		1			3
26	I	I-002	6.0	#1 OR #2A	2	11.2		1				3
27	I	I-003 (1st)	7.5	N/A	2 OR 3	11.2		1	1			3
28	I	I-003 (2nd)	8.0	#3	2 OR 3	11.2		1	1			3
29	I	I-003 (3rd)	3.0	#3	3	11.2			1			3
30	J	J-001	8.5	#1 OR #3	1 OR 3	15.4	1		1			1

Figure 1: A table of the logical sets based on ASTA data supplied.

4.2.1 The preferred model

We now discuss a model for scheduling the processing of logical sets of components over a monthly time horizon. The basic time unit in this model is a shift, and with a time period of a shift it will be necessary to assume that if a set of parts is scheduled in a certain shift it will consume all of the time in that shift. It is understood that this is largely consistent with ASTA's current scheduling practice.

Three sets of indices can be defined in relation to this model:

i	logical sets	$\{1 \ldots l\}$
j	autoclaves	$\{1 \ldots v\}$
k	shifts	$\{1 \ldots s\}$,

where there are l logical sets, v autoclaves, and s shifts over the scheduling horizon. The key decision variables in the model can now be defined as

$$x_{ijk} = \begin{cases} 1 & \text{if logical set } i \text{ is started in autoclave } j \text{ in shift } k \\ 0 & \text{otherwise.} \end{cases}$$

For a typical problem containing 30 logical sets, 5 autoclaves, and 60 shifts (3 shifts per day for a 20 day month), the number of decision variables is 9000, but if hourly periods are used, this number is 8 times that value. Autoclave logical set compatibility is defined via the array

$$a_{ij} = \begin{cases} 1 & \text{if logical set } i \text{ can go into autoclave } j \\ 0 & \text{otherwise.} \end{cases}$$

The demand for components in logical set i is given by b_i, where it is assumed that components can be scheduled at any time in the month. If it is necessary for certain logical sets to be completed at earlier times, the model can be readily adjusted to these requirements.

The model constraints are as follows:

$$\sum_{j=1}^{v}\sum_{k=1}^{s} a_{ij}\, x_{ijk} = b_i \quad \forall i \tag{1}$$

$$\sum_{j=1}^{v}\sum_{t=1}^{c_i} a_{ij}\, x_{ij(k+t-1)} \leq 1 \quad \forall i, \ \ \forall k \leq s - c_i + 1 \tag{2}$$

$$\sum_{i=1}^{l}\sum_{r=1}^{n_{ij}} a_{ij}\, x_{ij(k-r+1)} \;\leq\; 1 \quad \forall j,\ k \tag{3}$$

$$\sum_{i=1}^{l}\sum_{j=1}^{v}\sum_{k=1}^{s} p_k\, x_{ijk} \;=\; Z\,. \tag{4}$$

Constraint set (1) ensures that the monthly demand for each logical set i is satisfied. If c_i is the longest cycle time for tools associated with logical set i, then constraint set (2) ensures sufficient time for tools to be recycled by not allowing a like job to be scheduled during that cycle time. To illustrate, consider the case where logical set i can be scheduled only in autoclave j. Assume that the longest cycle time associated with tools in logical set i is $c_i = 3$. We assume then that tools used in this case are 'captured' for 3 shifts and will be available no earlier than shift $k+3$. Thus we have

$$x_{ijk} + x_{ijk+1} + x_{ijk+2} \leq 1 \quad \forall k \leq s-2$$

which ensures that i can be scheduled in only one of shifts k, $k+1$, or $k+2$. Note that if it is scheduled in shift $k+2$ for example, the constraint

$$x_{ijk+2} + x_{ijk+3} + x_{ijk+4} \leq 1$$

will also ensure that tools are not available until shift $k+5$, and so on.

In constraint set (3), n_{ij} is the number of shifts required to process logical set i in autoclave j. This constraint ensures that if a particular set has been scheduled in a particular autoclave in a given period then no other set can be scheduled in that autoclave at a time which would interfere with this schedule. To illustrate, consider the case of four logical sets where $n_{1j} = 3$, $n_{2j} = 2$, $n_{3j} = 5$ and $n_{4j} = 1$. For some general autoclave j and time period k, constraint (3) becomes

$$(x_{1jk} + x_{1jk-1} + x_{1jk-2}) + (x_{2jk} + x_{2jk-1}) + (x_{3jk} + \ldots + x_{3jk-4}) + x_{4jk} \leq 1\,.$$

Suppose $x_{1jk} = 1$, then this constraint ensures that $x_{ijk} = 0\ \forall i \neq 1$, and in addition, other logical sets such as 1 cannot be scheduled prior to time k in autoclave j if time period k is included in its cycle time. Equation (4) represents the objective Z to be minimised subject to constraints (1)–(3). In (4), if $p_k = k$ then there is a penalty associated with scheduling jobs late, and hence jobs will be scheduled as early as possible. This model is easily adaptable to interfacing with earlier schedules which might overlap into the current month. This can be done by simply setting appropriate sets of variables to zero, to block out the use of certain autoclaves. Another complicating factor which can be taken into account is the occurrence of interrelated logical sets, e.g. 10 and 11 or 13–15, which must be processed in sequential order and preferably within a short time of each other. Constraints which ensure this are not presented here.

The results of running this model (including sequencing of interrelated sets) based on the January demand data are shown in Figure 2. This solution took around 160 seconds on a Sun sparc station 20. Jobs with a demand of more than one unit are scheduled with sufficient time to allow for curing, unloading, return of the tool for another lay-up and reloading of the autoclave. Allowances for tool cycles can be increased if necessary if the schedule is seen to be too tight. Jobs which require more than one shift to process a unit are shown by a sequence where subsequent numbers have a negative sign, for example, job 6, AC5, on day 1. In this case the tools used on the A shift day 1 are recycled ready for the A shift on day 2; while the tools used on the N shift on day 1 are recycled for the N shift on day 2. A similar recycling process is ensured for jobs requiring sequential curing. Thus logical set 10 starting on the M shift in AC1 day 6 is followed immediately by set 11 on the M shift day 7. Note that the objective, which has assigned larger costs to jobs scheduled late, has resulted in jobs generally being processed as early as possible. This provides evidence of ASTA's true potential for processing jobs in January, since, of the 300 shifts available, only 187 have been required.

The model and the results presented should be regarded as simply an indication of the potential to generate realistic solutions to ASTA's autoclave scheduling problem. Several factors have not been explicitly modelled at this stage. These include possible labour constraints which may influence the ability to meet assumed lay-up cycle times, and conflicts in the use of the autoclave trolleys. Nevertheless, the model and its implementation has considerable flexibility to be adjusted to meet individual requirements of this nature if necessary.

4.2.2 Other IP models

Two other integer programming models were developed by the group. One of these will be briefly discussed but no mathematical details will be given. This model is set at a more detailed level than the one discussed in the previous section, involving six index sets, namely: n items (final assemblies), i logical sets, j autoclaves, k shifts, p parts, and t tools. Within a given time horizon (number of shifts), there is a requirement for a number of items n of this final assembly, and each item has a due date by which all the parts necessary to assemble that item must have been through autoclaves j. It is assumed prior to this model being run that all parts p necessary to make an item have been allocated to logical set i. All the parts in one set will be put through an autoclave together. Each part requires a tool t, and this tool is used from the start of lay-up to

Normal Requirements - Full packing to the beginning of the period

Day	Day 1			Day 2			Day 3			Day 4			Day 5		
Shift	M	A	N	M	A	N	M	A	N	M	A	N	M	A	N
AC1	2	25	17	30	25	1	16	25	1	2	13	1	14	2	15
AC2	26	22	-22	26	23	7	24	26	22	-22	12	23	7	24	9
AC3	27	19	28	20	29	21	2	27	19	28	20	29	21	18	-18
AC4	3	1	-1	-1	-1	3			3	7	-7	-7	-7	-7	
AC5	5	6	-6	5	6	-6	5	6	-6	5	6	-6	5	6	-6

Day	Day 6			Day 7			Day 8			Day 9			Day 10		
Shift	M	A	N	M	A	N	M	A	N	M	A	N	M	A	N
AC1	10	-10	-10	11	-11	-11	10	-10	-10	11	-11	-11	10	-10	-10
AC2	-9	22	-22	5	23	7	24	19	22	-22		23	5	24	6
AC3	19	27	20	28	21	29		18	-18	20		21	18	-18	19
AC4	3	7	-7	-7	-7	-7									
AC5	5	4	-4	-4	6	-6	5	6	-6	5	6	-6	4	-4	-4

Day	Day 11			Day 12			Day 13			Day 14			Day 15		
Shift	M	A	N	M	A	N	M	A	N	M	A	N	M	A	N
AC1	11	-11	-11												
AC2	-6	20	9	-9	6	-6	9	-9	6	-6	22	-22		23	
AC3	18	-18		21	18	-18									
AC4															
AC5	5	4	-4	-4	4	-4	-4	8	-8	-8	-8	-8	8	-8	-8

Day	Day 16			Day 17			Day 18			Day 19			Day 20		
Shift	M	A	N	M	A	N	M	A	N	M	A	N	M	A	N
AC1															
AC2	24														
AC3															
AC4															
AC5	-8	-8	8	-8	-8	-8	-8	8	-8	-8	-8	-8	8	-8	-8

Group	Count
1	4
2	4
3	4
4	4
5	11
6	11
7	5
8	5
9	3
10	3
11	3
12	1
13	1
14	1
15	1
16	1
17	1
18	5
19	5
20	5
21	5
22	5
23	5
24	5
25	3
26	3
27	3
28	3
29	3
30	1
Total	114

Statistics	
Shifts	187
Cont's	73
Diff.	0

Total Shifts	300
Spare	113

Negative numbers in the table opposite represent where a particular group of parts require 2 or more shifts to complete the group's autoclave processing.

Figure 2: An autoclave production schedule for January.

the end of the cure cycle. Labour required during curing has been ignored, but could be included if necessary.

Two sets of *continuous* variables and three sets of binary variables are used in this model. The two sets of continuous variables are:

$Lay_{p,i,n,k}$	the lay-up time (hours) used for part p of item n of logical set i in shift k
$Clave_{j,i,n,k}$	the cure time (hours) used in autoclave j for item n of logical set i in shift k

Thus the model does not restrict usage of an autoclave to one logical set per shift. If curing of one batch is completed early in a shift, a second batch can be put in the autoclave. Also if lay-up of one part is completed early in a shift, the remaining time can be used to lay-up other parts. The three sets of binary variables are:

$Use_{j,i,n,k}$	$= 1$	if autoclave j is used for item n of logical set i in shift k
$EndLay_{p,i,n,k}$	$= 1$	if lay-up of part p of item n of logical set i is complete by the end of shift k
$ForceCure_{j,i,n,k}$	$= 1$	if item n of logical set i has been in autoclave j in shift k and still has more than 1 shift to go

Constraints have been created which impose limits on labour availability, tool time availability, and the amount of curing time available for each autoclave in each shift. In addition, constraints are applied which ensure each logical set is cured for the correct time in the correct autoclaves, and that curing is completed by the due date. Another set of constraints ensures that once curing has started it runs continuously until completed, while there is also a set of constraints which force the curing of a set to follow, in time, the completion of lay-up of all parts in that set. The objective is in two parts. The first part seeks to minimise the work in progress by weighting the continuous variables according to the shift in which they occur. The second part minimises the number of shifts in which the autoclaves are used which helps ensure continuous use of the autoclaves.

The model was applied to a single final panel. An integer solution was found after around 15,000 iterations using GAMS/CPLEX on a SUN workstation, however no improved integer solution was found after 100,000 iterations and several minutes of CPU time. With several enhancements required and many more final assemblies to include, the prospects for this model yielding solutions in acceptable times seems remote.

4.3 Total demand and high volume products

One MISG group studied:

- The anticipated increase in demand for final products and whether that demand could be met from existing capacity.
- More detailed analysis of the scheduling of the manufacture of one product accounting for about 60% of demand.

4.3.1 Total capacities and demand

ASTA is fortunate in that it generally receives orders well before their delivery dates and that the orders are fairly regular albeit increasing. From forecast demand and production parameters it is possible to infer the total future demand for resources. The demands (in square meters-hours) for two critical resources, Bondshop Autoclave Capacity and Layup Room 2 Capacity, are given in Table 1. The Bondshop has capacity of 29,000, 58,000 or 87,000 if 5, 10 or 15 shifts are run per week. The corresponding figures for the latter are 23,300, 46,600 and 70,000.

The production parameters are the amount of each resource, such as labour, energy, floor space and times taken by various processes, required by each final product. Especially important resources are autoclave time since the autoclave cell is thought to be a bottleneck, and the time a part occupies a tool. Some of the production parameters are fixed (the autoclave cycle time) but others might be improved since the application of more labour might mean that a part occupies its tool for a shorter time. A shortage of autoclave capacity is thought to be a global production constraint. For each individual product there are relatively few tools on which it can be formed. The tools are expensive (of the order of $100,000). An upper limit on the production rate of each part can be calculated from the number of tools, typically one or two, and the time the part occupies the tool.

On the face of it, Table 1 suggests that the company would have enough resources to meet 1997's demand if it moved from 15 to 18 shifts. A critical issue is the efficiency with which these resources can be used. It is important to note that, because of congestion and competition for resources that are difficult to schedule, it is probably impossible for almost all factories to attain full utilisation of resources. For example, at ASTA, a shortage of parts ready for autoclaving might preclude full autoclave utilisation.

In other contexts it has been suggested that a factory can be usefully regarded as a device for which orders queue for service (Hopp and Spearman, 1996). Clearly, if orders are random, it is impossible to run the factory at 100% efficiency since the queue of orders would be infinite, and so a utilisation of 70–80% is perhaps more realistic. ASTA is informed of orders well in advance but has difficulty in efficiently scheduling its autoclaves. A utilisation of 80% might be a reasonable target; whatever the precise figure, ASTA should not assume that all autoclaves can be run 100% of the time.

Month	Autoclave Requirement (in thousands)	Layup Room Requirement (in thousands)
Jun 96	18	4
Jul 96	19	1
Aug 96	45	30
Sep 96	61	55
Oct 96	45	45
Nov 96	47	48
Dec 96	70	68
Jan 97	56	49
Feb 97	65	84
Mar 97	74	72
Apr 97	75	72
May 97	80	71
Jun 97	69	64
Jul 97	75	66
Aug 97	87	71
Sep 97	70	64

Table 1: Anticipated Resource Utilisation.

4.3.2 Scheduling an individual product

The MISG group noted that orders for a particular part, Component X, would, from mid 1997, absorb about 60% of SBC's total production hours. The fact that the demand was fairly regular, since ASTA would be required to deliver one Component X about every three working days in 1997, implied that this part's production could and should be scheduled regularly provided that competition with other products for resources could be managed.

The time required to make a Component X was, according to the company's MRP database, 44 days (production times of successive Component X's overlap). The group ascertained that, ignoring resource conflicts with other products, the critical path had length 146 hours. Making a part in close to the length of its critical path gives three advantages: some components have limited life spans prior to curing; working capital requirements are reduced if parts are made close to delivery dates and parts should occupy their tools for as short a time as possible. The last point is especially important. The tools themselves are expensive and occupy considerable scarce floor space.

Regularity is very desirable in a manufacturing context and ASTA should try to ensure that the regularity of demand for product Component X is reflected in that product's production plan. Provided there are enough resources, it should be possible, using MRP II or otherwise, to design a schedule for Component X production which comprises two overlapping production cycles resulting in one Component X being made every three days. The critical resources appear to be floor space (the parts and tools on which they are made occupy large areas) and tools. It appears that these are adequate to meet the demand of one Component X every 3 days.

It is hypothesized[3] that, with existing resources (in particular three tools for Component X) and a slight increase in efficiency, a Component X could be produced every two working days. This would require four cure cycles to be scheduled with high priority on autoclave number 2 every two days. A prerequisite for such a schedule is that the cycle time of 146 hours be reduced to 144 hours. The critical activity is tool utilisation. Tool's usage comprises a 125 hour occupancy by the part and 21 hour other, mostly cleaning. If this could be reduced to 144 hours, three six day cycles starting at two day intervals could be implemented.

If extra floor space and four tools were made available, it would be possible to have four Component X's in production simultaneously. It is possible, with precise scheduling of scarce resources (especially autoclave 2 which would be used in 23 out of every 24 shifts) to make parts in an 18 shift week. The company is aware of the resource problems and is considering them. The group felt that the orders for other parts could be satisfied by the remaining capacity.

The group did not consider the effect of variability of process times since the autoclave processing times are precisely defined. Appreciable variability would make scheduling, especially tight scheduling of the kind described in the previous paragraph, much more difficult to manage.

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[3] by Alan Brown

4.4 Modification of ASTA's MRP system

ASTA uses an elaborate Manufacturing Resource Planning (MRP II) system called MAN-FACT II. It was clear that any changes that the MISG study group recommended would have to be implemented in terms of this system. As modifying the SBC's use of this system may have implications for other centres, any modification must be carefully considered and tested.

This problem of scheduling the autoclaves efficiently was aggravated by the company's present use of MRP. MRP is at present used to schedule the production of parts comprising a final component so that they arrive in the assembly area simultaneously. They consequently pass through the autoclave cell at different times. As most of the parts comprising a final product have the same cure cycles, the opportunity to conveniently fill autoclaves with parts sharing a common cycle is lost.

After prolonged discussion with the company's representatives, the group recommended that *scheduling be autoclave centred* so that parts with the same cure cycle arrive at the autoclave cell simultaneously. The group felt that the disadvantage to the assembly function would be outweighed by better autoclave utilisation. The effect on WIP was unclear; there might, because of better timing, be less WIP in front of the autoclaves. This change requires that the MRP system be made to recognise logical sets and at least two suggestions as to how to do this were made during and after the MISG's formal proceedings. The two proposals are identified as using 'virtual work centres' and 'kitting-dekitting'.

The difficulty is that most MRP systems, in particular MAN-FACT II, are not designed to handle processes in which a number of parts must wait in order to be processed together. That kind of (batch) process is of course exemplified by ASTA's autoclaves. The situation is complicated by the fact that each part has a particular processing cycle which is usually shared by some other parts, and the packing problem — the desirability of filling an autoclave with parts which have the same cycle but different sizes and shapes. Happily, these complications were solved by enumerating logical sets of parts (see Section 4.1).

4.4.1 Using virtual work centres

This method entails the following steps:

- Each 'logical set' of parts will be associated with two work centres (work centre logical set or WCLS) which act as gate keepers for the autoclave(s) in which the logical set can be cured.

- All parts in a logical set will be routed from layup to a WCLS immediately preceding the autoclave cell (hereafter called the starting WCLS), to an autoclave and then to a WCLS immediately succeeding the autoclave cell (hereafter called the finishing WCLS). The starting and finishing WCLS's are fictitious, are normally turned off, and have infinite processing capacity. They are used to impose a schedule on the autoclaves decided elsewhere, e.g. by the methods of Section 4.2.
- If the schedule indicates that a logical set should start autoclave processing at e.g. 6 a.m. then the starting WCLS will be opened for one second at 6 a.m. thereby releasing a logical set (a full load) to the autoclave cell. If the cycle time is e.g. 15 hours then the finishing WCLS will momentarily open at 9 p.m. to release the cured logical set to the next process. It follows that parts cannot be worked on while being cured.

4.4.2 Kitting-dekitting

An ostensibly simple solution to the problem of batching parts in autoclaves was raised in discussion. A standard part of most MRP packages is to treat a collection of parts as a subassembly or kit. Once 'kitted' MRP regards the parts as a unit. It would be convenient to regard a logical set as a kit thereby forcing MRP to wait until the logical set was complete before it could be scheduled at the autoclave cell. However, ASTA representatives pointed out that if one component of a kit fails a quality test, the whole kit fails resulting in difficult to manage scheduling consequences.

After formal proceedings had finished, it was suggested that parts could be kitted to proceed through the autoclave cell and subsequently resume their original identities by being 'dekitted'. Dekitting is not available in MAN-FACT II but the package could perhaps be modified to provide that facility at unknown cost. Presumably, a faulty part would not affect the progress of other components of the kit. On the face of it, kitting/dekitting would work independently of the imposition of exogenous autoclave starting times.

If dekitting was available, the following scheme could be used to schedule autoclaves:

- If the logical set comprises only one kind of part (a rare circumstance) a fixed lot size equal to the number of parts in the logical set will be specified. MRP will not release parts to the autoclave cell until the lot is complete[4].

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[4] The 'F' (fixed) order policy (p. 216 of the MAN-FACT II product overview manual) can be used to ensure that only a full logical set is released to an autoclave.

- Where the logical set comprises more than one part, the logical set will be treated as a kit and dekitted after autoclave processing.
- The fact that the length of an autoclave cycle is independent of the load can be simulated by changing the MRP II database so that the autoclave setup time is equal to the actual cycle time and the run time is zero (or 0.0001 h).

5. Conclusions and further work

It was generally agreed that the deliberations of the MISG group resulted in positive outcomes for ASTA. These can be summarised as follows:

- The concept of a logical set of parts was defined, discussed and integrated into all approaches to solving the problem.
- The role played by the MRP II scheduling system was clarified and identified as a key factor in the problem solution process.
- Recognition that a few individual high volume parts contributed significantly to the consumption of resources.
- The development of Integer Programming models subsequent to MISG established the potential for this technique to contribute significantly in the future.

While much of the work done so far will influence ASTA's future thinking and their general approach to autoclave scheduling, tangible benefits can be achieved only by adequate follow-up work. Some additional work has already been commenced with respect to the high volume parts, and a proposal for the development of an integrated IP model to schedule all other parts has been presented.

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