Engine Production Systems in the US Defense Aircraft Industry

by

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ABSTRACT

A study was conducted, under the auspices of the Lean Aerospace Initiative, to determine the causes of increment in the production throughput time of engines in the US defense aircraft industry.

Three sites were included. The study was based on data gathered through interviews and review of engine build records at the sites. Besides engine characteristics, specifications and applications, emphasis was put on collecting data related to engine build spans, records of perturbations, factory floor layouts, and part flow paths. Particular attention was paid to the production scheduling systems used at the sites. Supply chain management and worker training and cross-training were also covered. Finally, a comparison was made between the policies implemented at the sites and the enabling practices of the Lean Enterprise Model

Results show how one of the studied sites achieves much better performance in terms of reduced build span variability and schedule conformance. Future improvement for the industry is also suggested.

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TABLE OF FIGURES

Acknowledgments

This work would not have been possible without the help of my fellow Research Assistants at LAI. Åsa Gabrielson and Auston Kilpatrick, who helped with the data collection at site A. Vicente Reynal's contribution, not only at all three sites but also at the analysis stage of the study, was crucial. Special thanks to my labmates, Haorong Li and Sam Truslow, with whom I spent precious days and nights working in the basement of Building 35.

I want to thank Tom Shields, co-lead of Factory Operations at LAI, for giving me the opportunity to conduct this research and for his great insight into the industry. I am very grateful to Dr. Steve Poulos, whose friendship and advice have been invaluable to me before and during my MIT years. To my advisor, Professor Timothy Gutowski, I owe more than to anyone else at MIT. His guidance and support have been priceless. I could not have had a better mentor.

I would definitely not have made it this far without the unconditional support of my family: my sisters, who have given me not only an exceptional example to follow, but the backing I have needed to succeed, and my parents, who will probably never know just how much they have done for me and how deeply I am in their debt.

To my mother, who taught me never to quit, and to my father, whose character, engineering genius, and integrity have forged and inspired me.

1 Introduction

What is lean? Since the 50s, many developments have taken place in the automotive industry that have had one objective in mind: the reduction of waste. Changes were achieved through the application of science and technology (engineering) to solve manufacturing problems which involved intrinsic waste, thus in the automotive industry lean has taken a certain shape and character. It is often thought that the principles of lean production, so successful in the automotive industry, would be very hard to implement in other industries. Aircraft manufacturers argue that their production systems deal with completely different products and requirements and that as such, are not candidates for lean production such as achieved by Toyota. They could be right. It is certainly tough to convince oneself of the contrary when a company makes a dozen units a year, compared to a car manufacturer which might have an equivalent period production 5 or 6 orders of magnitude higher. Aircraft also have tremendous differences with automobiles in that their lifespan is approximately 10 times greater than that of a car and the consequences of a failure can be catastrophic, thus, expected reliability is also several orders of magnitude higher. The same exact ideas simply won't apply directly in both fields.

However, it has not been proven that there is a fundamental reason why the general philosophy pioneered by the founders of the Toyota Production System half a century ago could not be applied now by a different industry. While the aircraft industry does in fact deal with different variables and rules, they do the same thing any manufacturer does: they produce goods based on designs and they use many different parts made of a variety of materials and which themselves are made in many different places. This complex process has wastes, just like the auto industry in general had 50 years ago. Why could we not come up with solutions that reduce this waste? We are still dealing with people, materials, machines, assembly and scheduling systems. What we must do is apply what we have learned from lean production systems in place, apply what corresponds to the new systems we are trying to improve, and develop new solutions where current ones do not work in the new environment.

This thesis shows an example of a system that deals with products that are very different from automobiles; jet engines. It proposes the hypothesis that these principles can in fact be applied to the aerospace industry. We will see one case where the application of existing methods, and the development of new ones, is helping to steer a production system in the correct direction; that which reduces waste and meets the functional requirements of the production system; reliability and 100% on-time delivery. The author hopes that the results shown in this study will help steer the entire industry in this direction as well.

This study was undertaken by the Factory Operations Focus Group of the Lean Aircraft Initiative at the Massachusetts Institute of Technology. It was launched with the goal of identifying assembly time perturbations in the engine sector of the US Defense Aircraft Industry. The production of engines at three sites was analyzed and data were collected from October 1996 to January 1998. Besides engine characteristics, specifications and applications, emphasis was put on collecting data related to engine build spans, records of perturbations during assembly, factory floor layouts, and part flow paths. During this study, the throughput time of over 300 engines was recorded. Details of the perturbations of 33 engines were also captured. In all, 135 man-days were spent at the sites collecting data. Particular attention was paid to the production scheduling systems used at the sites. Supply chain management and worker training and cross-training were also covered. Case studies, which later formed the foundation for this final work, were written for each site. It is the privilege of the author to be the chosen participant to present the results herewith.

2 Aircraft Engine Assembly

Product Description

Jet engines are the primary source of power for aircraft nowadays. Ever since they were developed in the 1930s they have continued to evolve and now some of them produce almost 90 times the thrust that the Heinkel HeS-3b did in 1939.

The three companies included in this study have produced aircraft engines for the past 60 years. In 1926 Pratt & Whitney received its first order from the US Navy for the Wasp model, a 425 hp reciprocating engine. Allison Engine company delivered its first V1710 engine to the Navy in 1932. In 1942, the General Electric I-A was the first jet engine built in the United States. These three companies have long since been involved in the production of turboprop, turbojet and turbofan engines for the aircraft industry.

During this study we focused on 6 particular engine models. Three of them are for military use and the other three are for the commercial market. Table 1 shows a summary of the most important characteristics of these engines.

	engine A1	engine A2	engine B1	engine B2	engine C1	engine C2
number of part numbers	~2,000	~2,000	~1,400	~1,300	4,465	3,485
total number of parts	~15,000	~19,000	~7,000	~7,000	26,073	23,580
weight [lb]	2.3k-3.5k	9k-10k	1.5k-1.6k	1.5k-1.6k	2.3k-3.5k	1.5k-1.6k
thrust [lb] unless otherwise noted	14k-21k	40k-50k	4k-5k hp	7k-9k	14k-21k	7k-9k
by-pass ratio	0.36:1	4.9:1	-	5.15:1	0.34:1	6.2:1

	engine A1	engine A2	engine B1	engine B2	engine C1	engine C2
annual production	150	150	110	150	150	286
planned through-put time [days]	15	20	8	10	23	21
approx. takt time [shifts/engine]	7.30	7.30	6.64	4.87	4.87	2.55

Table 1 - engine characteristics comparison

Jet engines are quite complicated products. The number of parts that go into them is in the tenths of thousands range. Figure 1 shows a drawing of a military fighter engine and the location of its major subassemblies or modules.

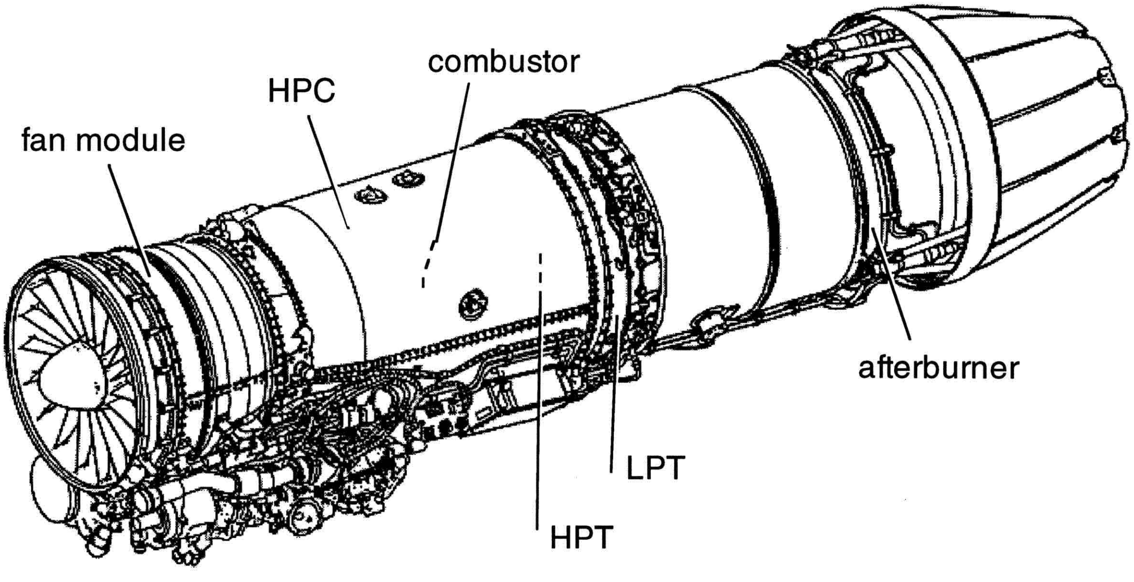

Figure 1 - military fighter engine

Commercial engines are similar in many ways to military ones. Military engines are designed to deliver the maximum performance possible. They also have an afterburner, which is not the case with commercial engines. In the commercial world, durability, maintainability, noise and price have a slightly higher priority than they do in military aircraft. Many of the engine stages are the same, but the performance goals are different. Figure 2 is a cut-away drawing of a commercial engine.

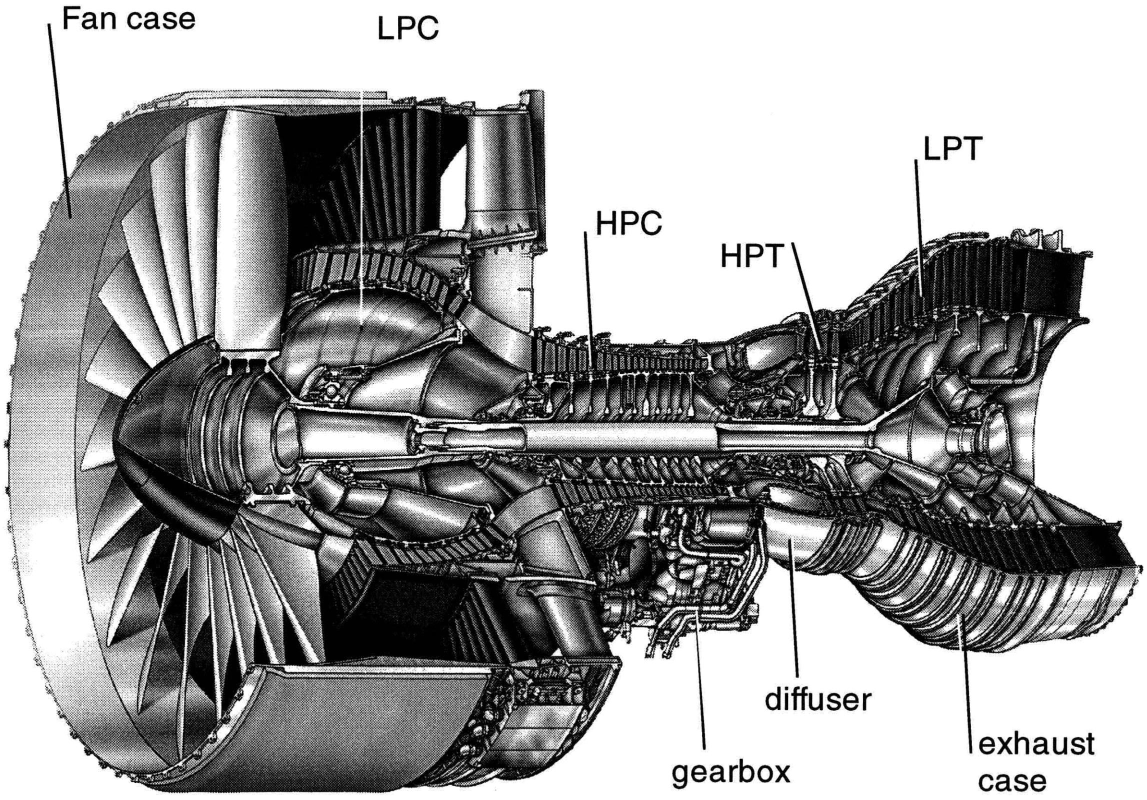

Figure 2 - large commercial engine section

Commercial engines also have a by-pass ratio about an order of magnitude greater than do military turbofans. Larger by-pass ratios require larger fans, thus requiring more turbine stages to drive the heavier, larger fan. The higher the by-pass ratio, the higher the weight, fuel comsumption, and the lower the thrust become. In military aircraft the by-pass ratio is determined based on the type of mission the aircraft is designed to fly. Aircraft that require longer range need to have higher by-pass ratios the same way that fighters that need high acceleration require lower by-pass ratios. Another difference, as an engineer at a site eloquently put it, is that “commercial engines are not designed to be shot at”.

The engine in figure 2 powers large commercial transports. During this study the assembly of smaller commercial engines was also analyzed, such as those used in commuter or business jets. Figure 3 is a cut-away drawing of such an engine.

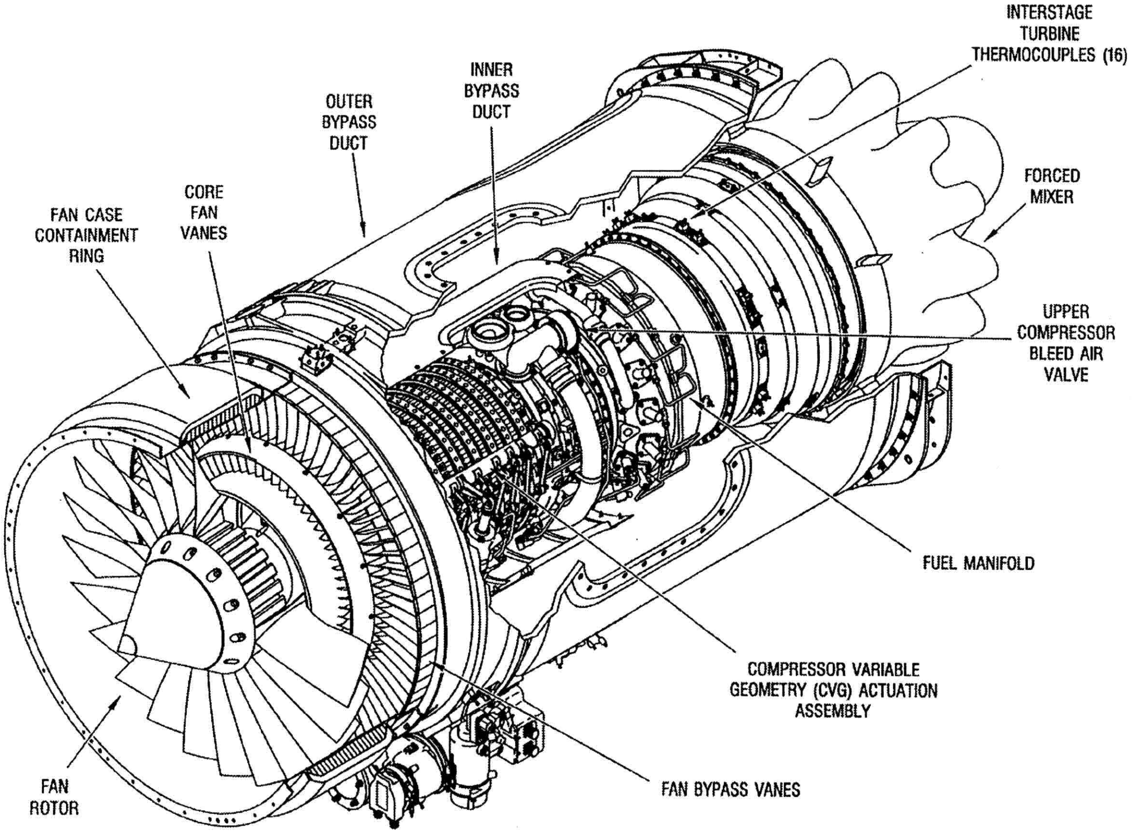

Figure 3 - small commercial engine

Plant Layout

Layout is one of many variables that affect the performance of a production system. Nevertheless, the way in which the layout of a plant is designed has an impact on the ability of products or parts to get through it with few perturbations. All other things being equal, a factory where parts have to travel complicated paths and long distances will be more likely to have long throughput times for products, and perturbations which cannot easily be fixed. When flow can be visualized in a simple way, i.e. processes are next to each other, next steps are easily determined, and parts will tend to spend less time in the system. In addition to this, perturbations in the process will not cause chaos as easily since the problem will be easier to detect and therefore will be fixable sooner.

Figure 4 shows the plant layout at site A. Common types of subassemblies for various engines, i.e. high pressure compressors, are all built in the same area of the plant. That is, assemblies are distributed by function or type rather than product line. Accordingly, subassemblies are usually batched, and have to travel relatively long distances within the plant until they can be put together as an engine.

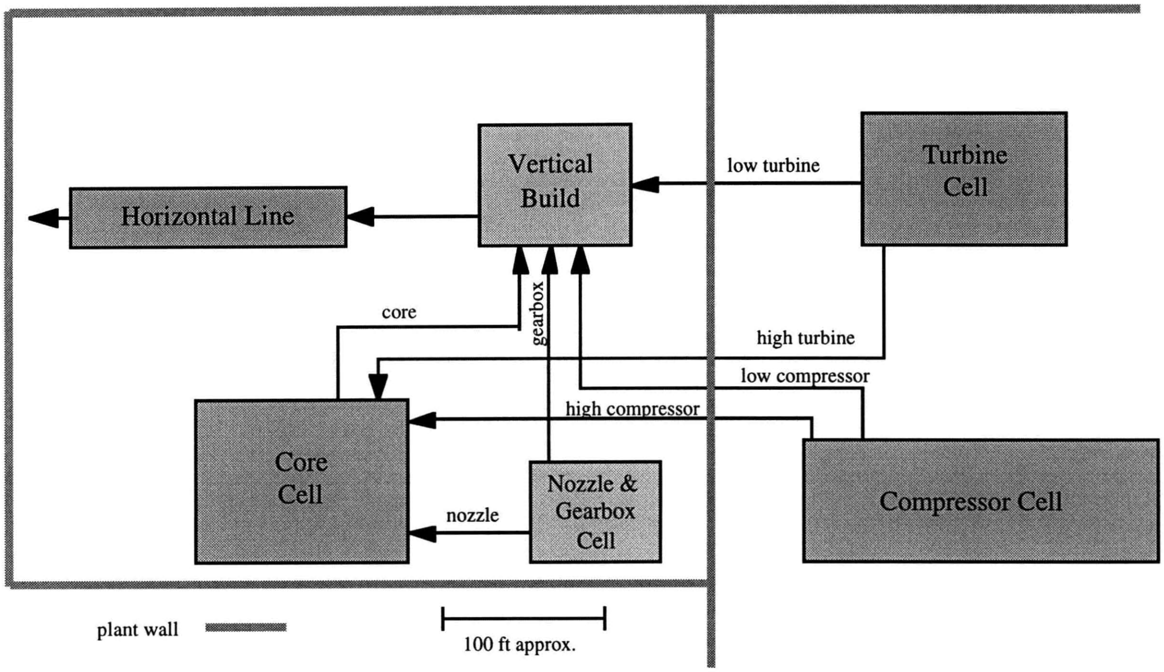

Figure 4 - plant A layout

This job shop environment was implemented to share fixtures and tools which where designed for one type of assembly and personnel who where trained to do one type of build. There are some instances when a job shop environment can be a better solution than dedicated product lines. Such instances include very customized production, for example, a plumbing assembly plant where a thousand different models of plumbing assemblies are done. If the layout were to be done by product, the logistics would be extremely complicated. Distributing tube-bending machines along the 1000 different products would not be possible. Also, some of those models might not be required but once every 2 months and in small quantities. The lines that produced these models would not be utilized during that entire time. In these cases, it might make more sense to distribute machines by function and have parts flow through these stations. It should be noted that job shops tend to maximize the management performance measures such as machine and people utilization.

However, in a factory that assembles units which can be produced in approximately a dozen different ways, such as an aircraft engine plant might be, dedicated engine lines are a better solution because they allow for easier detection of perturbations and traceability of root causes. A proposed layout for site A could be to implement one such as the following, shown in figure 5.

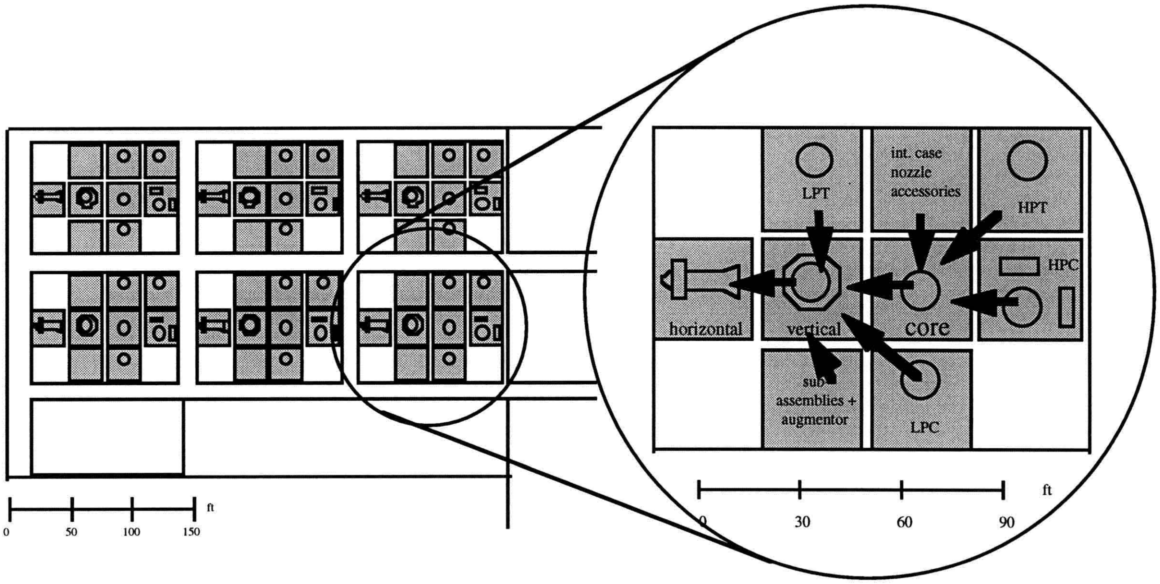

Figure 5 - suggested dedicated line layout for site A's case

Site B has a similar type of arrangement as site A, in that engine modules are assembled by type, rather than by engine model. Figure 6 is a diagram of the distribution of these assembly areas within the plant.

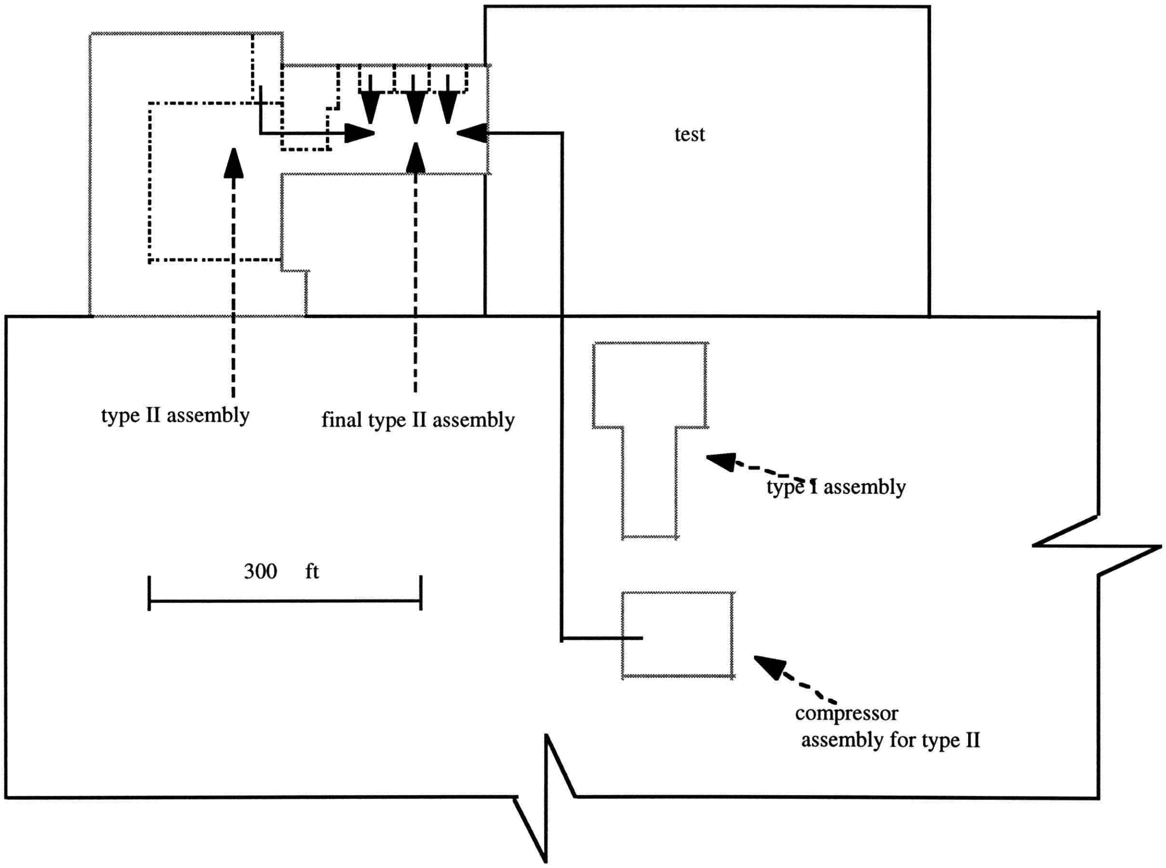

Figure 6 - plant B layout

For plant B a proposed layout with dedicated engine lines might look as shown in figure 7 where two kinds of engines could be assembled.

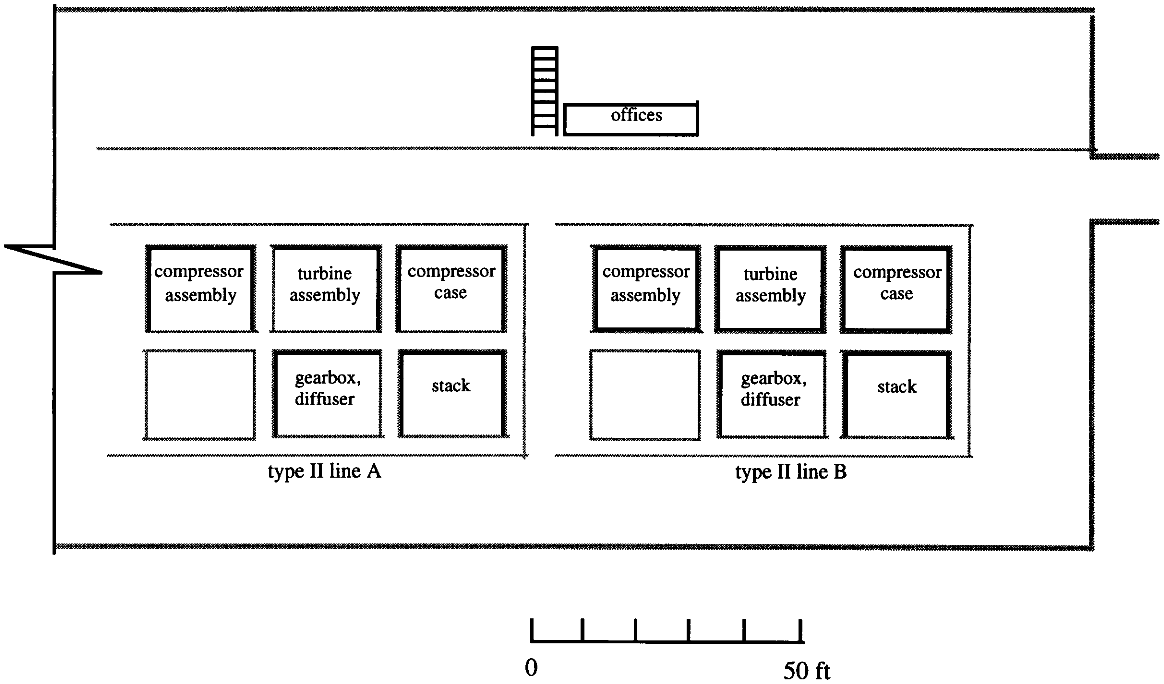

Figure 7 - proposed layout, plant B

The layout at site C is quite different from the other two. Here, engines are built within dedicated production lines. All modules of an engine are built within that assembly line. The exception to this is the location of large grinding machines which require special foundations and cannot be easily relocated on the floor. These machines are shared by all engine lines. Figure 8 shows a general diagram of this layout.

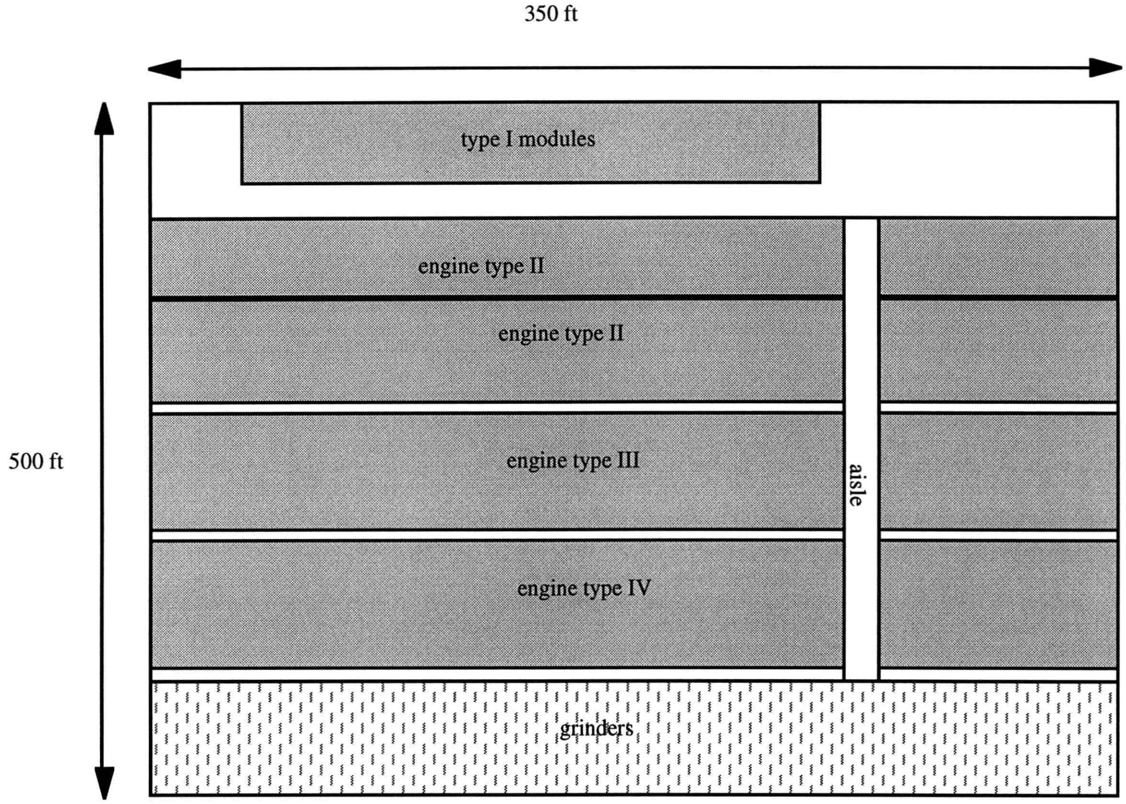

Figure 8 - assembly plant C layout

With this kind of arrangement, parts travel shorter distances inside the factory and paths are not as complicated as with a departmental distribution, seen in sites A and B. Within these dedicated lines, smaller assembly areas, approximately 20% the size of the ones seen in departmental arrangements, build individual sub-assemblies only for the engine type of that line. The fact that the number of available build-stands for modules is limited, makes it easier to detect if a module is experiencing delays. When assembly room is very large, if a module suffers from delays, it can simply be put aside and worked on at a later time while other modules are built. In this kind of system, finding the problem that caused the delay may not be a very high priority since other builds can continue. On the other hand, when only a reduced number of build stands are available, delays need to be understood quickly, since there is no room to build up inventory. This creates a system that finds out about its problems sooner and can target them faster. In fact, it must target problems sooner, because this system is very intolerant to disturbances. The limited number of build stations, for example, at a sub-assembly area in an engine line only allows for a certain number of modules to be under assembly. If they experience a delay, no other modules can be built in the meantime.

Summarizing, we saw three different arrangements of factories to assemble engines. The characteristics of them are shown in table 2. While some of these sites included areas where parts were produced, only the assembly buildings were taken into account to calculate the following data. The numbers in table 2 are approximate to within 5%. The third row shows the distance traveled by an engine normalized by 15,000 parts. That is, the average distance traveled by an engine divided by the number of parts of that line's engine and multiplied by 15,000. There is roughly an order of magnitude difference between the value in this row for site B and C. In a dedicated product line environment, parts simply do not travel as much as in a job shop environment.

	site A	site B	site C
assembly area [ft^2]	290,000	125,000	175,000
average distance traveled by engine [ft]	1,800	2,500	1,400
distance traveled (normalized per 15,000 parts)	1,590	5,360	845
layout type	by process	by process	by product

Table 2 - main characteristics of assembly facilities

Assembly Process Description

Once all the needed parts are at the plant, assembly of an engine does not require highly complex machinery, tools or robots. It is mostly done with conventional tools and hydraulic presses. Parts that are too large or heavy to be handled manually, are moved by gantries. Other machinery that is used frequently during the build are balancing machines, to balance rotors and grinding machines that grind the outside circumference of rotors once they have been assembled.

Parts for builds are stored in trays or boxes which are put on carts or shelves. Operators generally use tables to lay out the parts which they will use for a build. If the build can fit on a table, they will use one for the assembly. However, some builds are too large and/or heavy and need to be assembled on large jigs or special carts. Larger elements of the engine are assembled on an elevator which can either raise or lower the engine so that the operator can work on the upper portion of the build, or lift or lower the operator in respect to the engine.

Figure 9 shows a general process map for the assembly of a jet engine. This map does not reflect the process used at a particular site, but merely the general distribution of subassemblies and the order in which they are assembled to form an engine.

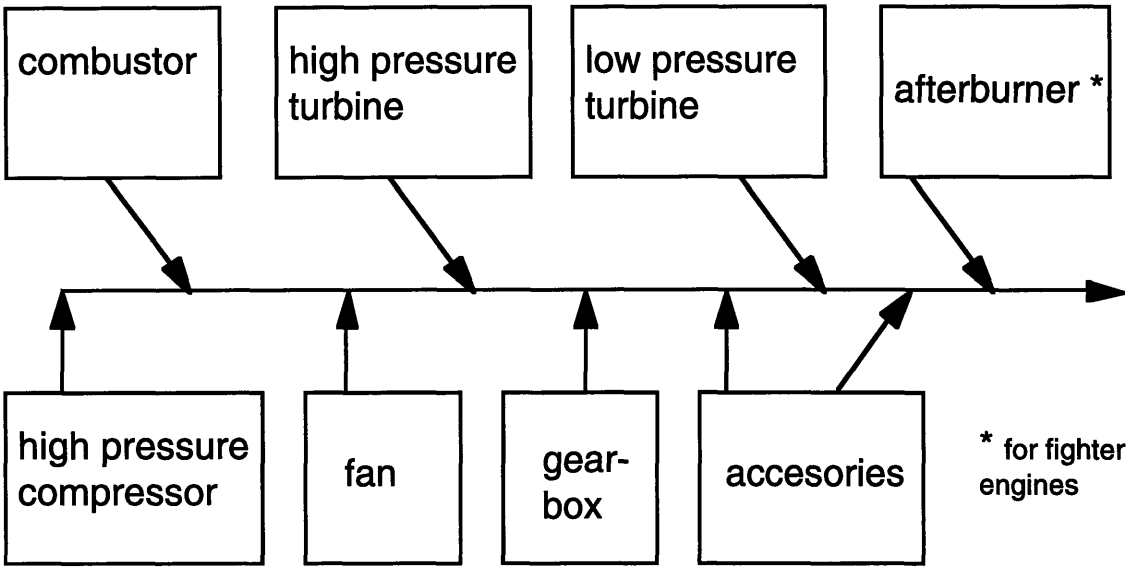

Figure 9 - general process map for assembly of a jet engine

Subassemblies vary from a few dozen parts to thousands in the case of a compressor or turbine. They take between 4 hours and 2 days to complete. When rotors (part of compressors and turbines) are assembled, they are balanced in several ways. First, the blades are distributed along the circumference in accordance with their actual individual weight. Balancing machines are used to verify the balance of the assembly and weights are used to compensate when needed. Balance is a crucial step in the assembly of engine rotors and most important for its performance.

Usually one operator will be assigned to a particular build if it deals with a small subassembly. However, with larger builds, such as vertical stacking of components or assembly of larger engines, two operators will be in charge of the task. Operators use assembly sheets as a guide for the build. These sheets contain the instructions needed to complete the build in the correct order. They also instruct the operator to seek inspection when required. When an inspector is called to the build, he or she will review the specifications for the build and measure or gauge the unit. The inspector will then either approve or reject the build.

The process maps for the particular engines covered in the study are included in Appendix A. The detail with which the maps could be produced depended on the site and how the individual plants sub-divided their assembly steps.

Human Resources Management

Performance Measures

The most important asset of a production system is its people. The system can only be productive if the system's interests are concurrent with the workers interests. That is, workers, managers and suppliers must have motivation to perform tasks in a way and timing that end up benefiting themselves and the system. For instance, a system that intends to have a certain production rate must have incentives for people to produce at that exact rate. If the performance of an assembly team is only based on the number of modules it produces, the people in the team will simply produce as many modules as they can. Inventory between that build area and downstream stations will start to build up.

In order for a system to function properly, all of its sub-systems must have the same goals as the system. The suppliers at the time of the study were about a month and a half behind schedule on average. One possible way to recover from this backlog would be to stop production until part delivery could catch up. Nevertheless, if management were to implement such a policy, a decrease in production would be experienced (at least for a transitional period). If during this period management were still judged according to the traditional performance measures (engines produced to MRP schedule), they would appear to be doing a poor job. However, if this policy were to benefit the company in the long run, a fresh approach to management evaluation would be required. Of course, stopping for production for 50 days or so is not the solution either. It would be extremely hard for a system to survive without having any production during that long a time. The first step in any effort to stabilize the production of engines, thus reducing the variability in engine assembly time, must be aimed at improving the supply chain so that parts arrive when they are needed; not one and a half months late.

At site B, upper management's performance is measured based on the number of engines delivered during a month compared to the number of engines scheduled to be delivered during that month. While at site A sub-assembly leaders were also judged on their conformance to MRP schedule, their counterparts at site B were not. At site C, the performance of management and everyone involved in the build is measured based on their conformance to the planned schedule. The difference between the performance measures at sites A and C is that the schedule at site A is fixed. Thus, when delays occur, a subassembly area leader might be doing very poorly according to MRP; he will not be producing the modules, for instance, he was supposed to that week. But it won't be his fault, since he has no control over parts availability.

In the case of the supply chain, it is imperative that the supplier have the correct motivation to deliver in a manner consistent with the production system goals. For instance, if a supplier delivers a set of 50 blades for a rotor, which needs 60 blades, the rotor will not be able to be assembled completely. It would be useless much like a table with 3 legs. In sites A and B, suppliers (internal and external) can deliver partial sets of parts and get compensated for it. In site C, suppliers deliver complete kits of parts only. One could argue that suppliers could deliver any parts they have as soon as they become available to speed up assembly. However, as we will see later in chapter 4, site C, where kit deliveries are made, outperformed sites A and B by an order of magnitude. It would appear that partial deliveries, as done at sites A and B, do not contribute to expedite assembly in this case.

Wages and Incentives

The following is an example of the incentive system at one of the sites. This particular research was conducted at site A by Åsa Gabrielson of MIT.

> "The wages of hourly workers are determined by the labor grade they have achieved, and the labor grade is formally dependent on an evaluation of the complexity of the job. All employees in one work area have the same type of job code, or occupational group, for example Machine Operator or Assembly & test

> Inspector. Within each job code there may be different labor grades. Each work area has a fixed set of labor grades depending on what tasks are performed within the area. A labor grade 2 worker should be more skilled and perform a more complex job than a labor grade 4 worker. An hourly worker's possibility to achieve a higher labor grade is almost totally dependent on his/her seniority. If an extra labor grade 2 worker is needed in a work area, the labor grade 4 worker with the highest seniority automatically gets this job, even though the person may not be the most suitable. If the labor grade 4 worker does not have enough skills or is not willing or capable of acquiring the skills, the job offer goes to the next person in seniority.
>
> This wage system does not promote flexibility. Instead, it may in some cases even hinder it. With the exception of dinner tickets worth $75, there is no formal incentive or bonus system for hourly workers. Thus, the only possibility for hourly workers to earn more money is through overtime. This reveals an implicit incentive: don't deliver on time so that we can work overtime. A better designed wage and incentive system could send signals that are more in line with a lean manufacturer."
>
> Source: Åsa Gabrielson, Human Resources At site A

Training

As mentioned before, a well trained worker should be considered the most important part of a production system. He or she, being well trained, will be able to do different jobs and hence provide a high degree of flexibility to the system. His or her flexibility will play an important role in the flexibility of the system to deal with a changing environment and a varying demand as well as perturbations and eventualities. If workers can, for example, assemble a compressor as well as they can balance a turbine stage, assemble an afterburner or join a combustor to a turbine, the system will be more flexible than if the same worker could only do one task. If a perturbation forces a higher work load in a particular step of the assembly process, worker flexibility will be crucial in determining whether the system can recover from the problem without suffering major delays.

Worker flexibility is an issue with which each site is wrestling. Union rules tend to protect worker rights by limiting work assignments. The sites visited are working with the unions to increase worker flexibility. Ways in which this was done were: reduction of the number of classification and broadening the area in which classifications could perform work tasks. Despite these gains, we noted work restrictions on tasks that could be accomplished with worker cross-training. It should be noted that all three sites have unions.

> "Formerly, there was a Job Training Center (JTC) at site A which was responsible for all the training of hourly workers. The JTC also had other duties such as summer courses for students in order to create an interest for future employment. Due to down-sizing, the JTC was closed and job training fell outside the main focus of priorities.
>
> Site A has now started mapping which competencies exist and which are needed within each work area. This is a very good initiative and it is important that the competence matrices are kept up to date with a minimum of administration (facilitated by documentation, for example, in electronic spreadsheets). From a quality perspective, however, it is noteworthy that there is no mapping of knowledge in quality improvement tools. Also, from a flexibility and internal recruitment perspective, it would be interesting to document skills outside the current work area.
>
> The Job Training Program (JTP) is a result of negotiations between the management and the union at site A. The supervisors put up yearly training plans in cooperation with the personnel. What effects the JTP will have is dependent on management's support and involvement.
>
> The wage and career system promotes, in principle, only seniority. If the workers stay within the same work area during their employment, they not only increase chances to get higher wages, they also increase their job security. If the workers instead want to develop new skills and work in another job code, they will not be able to raise their wages as quickly as in the first alternative and they will lose job security. Thus, the flexible worker gets lower wages and has less job security than the worker who has stayed within the same job code during his/her employment. This can be compared with other wage and career systems which, in line with

> increasing demands of a flexible and multi-skilled work-force, clearly promote a certain level of flexibility among the personnel.
>
> Also, there are some hourly workers who are trained in work tasks outside their job code. However, there is no mapping in the competence matrices of what tasks the hourly workers may know besides the tasks within the job code."
>
> Source: Åsa Gabrielson, Human Resources At site A

Again, as discussed previously, it would be reasonable to suggest that a good way to approach the problem of flexibility would be to motivate workers to be trained in as many tasks as possible, since that is beneficial to the system. In sites A and B, advancement in training is not encouraged and does not affect worker compensation. In site C there is a slightly greater motivation, since workers can train to perform other tasks and get compensated for it, but this is limited to duties within their work area because of union work rules.

Another important aspect of worker training is not only the number of tasks he or she is trained to perform, but also the way in which he or she was trained to do those tasks (quantity and quality). Throughout the industry, training is mainly on-the-job. However, at sites A and B, training is a bit less formal than at site C, where workers are identified as particularly skilled in the training of a build. Only these workers can train someone in those kinds of builds. There, new workers are assigned to the instructor correspondent to the build they will learn. At the end of the training, the trainee also evaluates the trainer. In sites A and B, trainers are not identified with a particular build with which they are specially good.

A defect of the training in all three sites is the lack of instructional documentation, such as guidelines that can remind an instructor, every time he will train a new worker, of the most important aspects of that build. If all the instructor has to rely on is what he remembers as important, with time, knowledge is lost and the critical parts might not be viewed as important as they should be.

There was a difference in the way work was organized at the sites. While sites A and B had a three shift operation, site C only had two shifts (each sift consisting of eight hours). As seen in table 1, the annual production at the three sites (for the engines studied) was

300 at site A, 260 at site B and 436 at site C. In fact, site C is the one that produces the most engines, but only has two shifts. There was a relatively high level of overtime at sites A and B as well, while almost no overtime was needed in site C.

3 Scheduling Systems

Management of a production system can be broken down into three main components:

- available resources (people, facilities, machines, material, etc.)
- distribution of resources (factory layout, job assignments, etc.)
- scheduling system (what is done when)

In this chapter, the last component will be discussed. The way in which a production system is scheduled is as important as the means it uses for production. The correct scheduling system can harmoniously coordinate the different parts of the production system while the wrong one will cause disruptions, delays and confusion about the real problems the system faces.

We observed two basic types of scheduling systems at these sites: Material Requirement Planning system (MRP) and Kanban. MRP[1] systems have been installed in many production systems. The reason is that MRP is a logical and easily understandable approach to the problem of determining the number of parts and amounts of materials needed to produce a particular number of end items. MRP also produces the time schedule specifying when each part should be produced or ordered. MRP is based on dependent demand, which is caused by the demand of a higher level item. For example, electronics, engines and landing gear are all items which depend on the demand for aircraft.

A later version of MRP was called Manufacturing Resources Planning, or MRP II. This system also schedules other resources, such as people and machines, in the production system

The main deficiency of MRP is that it doesn't leave room for perturbations, the one inevitable element in any manufacturing system. It also assumes infinite capacity, which

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[1] from Chase and Aquilano, Production and Operations Management.

is not realistic. Since there is little feedback to the schedule when a delay occurs, MRP assumes production has not been hindered and keeps pushing material onto the factory floor.

Kanban production is based on a control system that is simple and self-regulating. The factory floor - supplier release and control system is called *Kanban*, Japanese for card. It is paperless and uses containers and cards. The system relies on the authority to produce or supply coming from a downstream process. There are two types of Kanban cards. The production Kanban authorizes the manufacturing of units that fit in a container or bin. The withdrawal Kanban authorizes the removal and shipment of that container to the next downstream process. Kanban hinges on everyone doing exactly what is authorized.

Site A - Push with MRP

The scheduling system used in site A is based on MRP. Engines at site A are built to order. That is, once an order is placed for an engine by a customer, the scheduling of the engine build is done. For this purpose, site A uses an MRP system that determines when each module for that particular engine needs to be started. Dates are determined for the ordering of materials needed for the engine and the build is scheduled on the factory floor. This does not mean that the build can take place immediately. Usually the plant has other engines that need to be assembled that were previously ordered. The current time from when the customer places an order to when the engine build is begun on the floor is approximately 9 months. The MRP system determines the dates when modules have to be begun and finished. It does not take into account how many modules might be stalled in the assembly areas due to production delays and part shortages or other perturbations. Figure 10 is a diagram of the scheduling system used in site A.

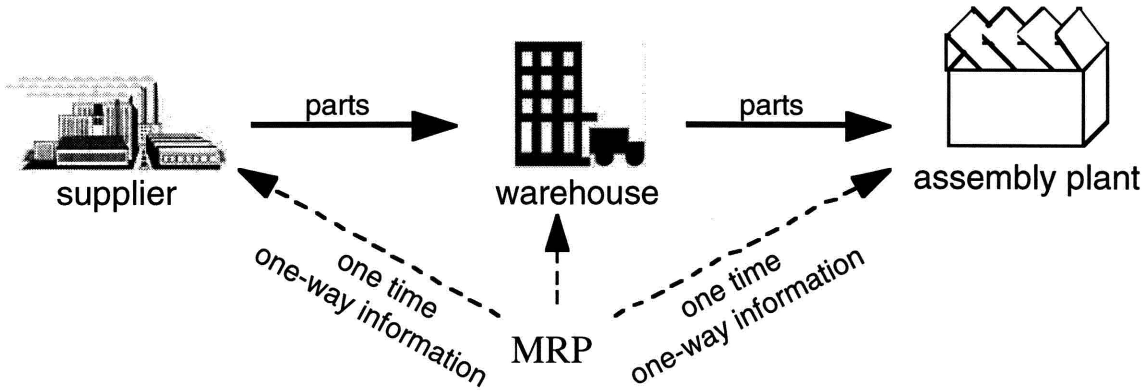

Figure 10 - scheduling system at site A

Every morning, assembly area leaders meet with the Materials Manager and discuss the status of modules for various engines. At this meeting priorities are established for the build of engines. Those that are lagging further behind in their delivery dates have higher priority. Based on this information, assembly area leaders know how to prioritize the modules they are building and allot resources to those that will be most needed in the downstream assembly stations. MRP also determines a date when the engine is due to be completed. However, the contract date for the delivery of the engine is approximately one month after the engine MRP finish date. Site A makes every effort to be able to deliver engines by the contract date. When they can't meet this deadline, penalties are paid to the customer. At the time of this study, contract dates were being met at site A approximately 65% of the time.

Site B - Push with Monthly Batches

Engines at site B are built to forecast. The sales department tries to predict what the engine demand will be for the next couple of years and based on this figure engine production is scheduled. Some of the parts that go into these engines have very long order lead times[2]. While the average is approximately 11 months, some of the more complicated parts can take as long as 14 to 17 months.

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[2] lapse from the moment when an order is placed to the time it is delivered.

Every month a bi-monthly schedule is released which contains the number of engines that have to be produced during each of those months. All of the commercial engines scheduled for a specific month will be due on the last day of the month. Military engines, however, do have a due date within the month. It is up to the area managers to distribute the work over the entire month. Parts needed for a month's engines are required to be on-site the first day of the month. If at the end of a month there are unfinished engines, these will be put on the next month's schedule. Figure 11 shows a diagram of the scheduling system at site B.

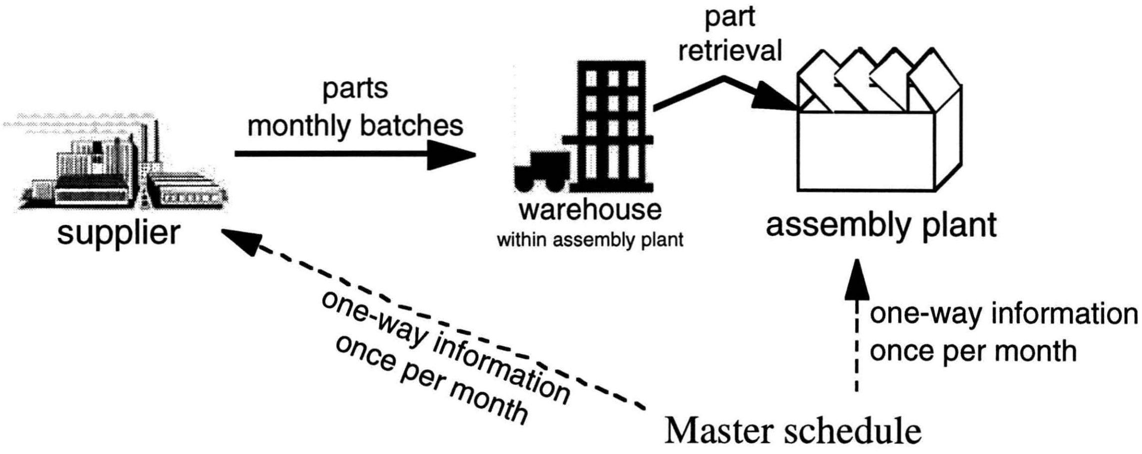

Figure 11 - scheduling system for site B

The scheduling system currently used at site B is called "Optimized Production Technology" (OPT). In theory, one of OPT's main focuses[3] is that the output capacity of a production system is controlled by the processes that have the least capacity. The objective is to control the flow and inventory levels in the system to ensure that the bottleneck[4] does not stop working because its output is directly related to the output of the system. However, the assembly part of the system is not controlled by OPT. The purchasing of parts from external suppliers also does not go through OPT; only raw materials do. The lack of synchronization between supply and assembly causes disruptions and confusion. Foremen have to improvise when a decision has to be made on which build to begin or continue.

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[3] from Chase and Aquilano, Production and Operations Management

[4] that process which has the least capacity of all.

Every morning at 7:15 there is a meeting attended by assembly managers, area managers, foremen and representatives of the fabrication divisions. The main subject in these meetings is the progress of the engines due for that month and the discussion of the 20 most important part shortages related to those engines. That is, the most important individual parts that have not arrived from the supplier and are holding up the build of engines. It will be shown later in chapter 4 how this system affects the delivery of finished engines.

Site C - Hybrid with 80% Pull

The systems we have seen in sites A and B are mainly push systems. That is, material keeps flowing whether there is capacity to process it or not. In site C, however, the system in use is different.

Site C uses a hybrid scheduling system. While some parts are scheduled under an MRP system from the suppliers, 80% of the total value-worth of parts is supplied under a pull system. It was reported that the warehouse size has gone down as more parts are added to the pull system. It is also going though a reduction in size. For each of these parts there are three bins total. One of them is usually on the floor ready to be worked on, another one is at the plant on stand by and the third is being filled at the supplier end. This production sequence is a pull system, which is based on the authority to produce or supply, coming from downstream processes. Figure 12 shows a diagram of the hybrid scheduling system used at site C.

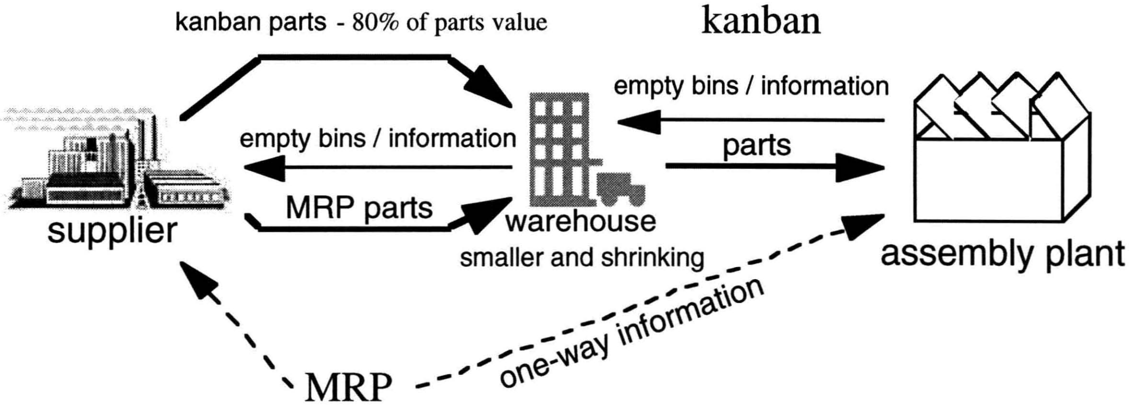


Figure 12 - site C hybrid scheduling system

Two weeks prior to the beginning of the month, customers are called and the exact number of engines they'll require is checked, the number is frozen and the engines are scheduled for next month. This has the advantage that production for that month is now fixed and accurate scheduling and planning can be done which will allow for smooth operations at the plant. Every year communications are made with customers to try to determine what the engine demand of that customer will be for that year. Based on this, a preliminary schedule is made with monthly production requirements for each customer. Generally, actual production is within 10% of the yearly prediction. The reason for this is that assembling an aircraft is more complicated and takes longer than the assembly of an engine.

Every day at 7am, 3pm and 11pm there is a meeting of each line team which is attended by the Line Leader, who is in charge of the entire line, the supervisors, and the lead men. At these meeting they discuss the work distribution for the next shift for that line. These meetings last about 15 minutes. Usually the Line Leader will prompt each attendant to voice their concerns about production. At 7am there is a meeting attended by the assembly leader and the material managers. Issues of overall importance to the assembly are brought up at these meetings.

Part Release

Another important aspect of scheduling policies is the one that addresses the release of parts to the factory floor for assembly. In theory, a part that is stored in a warehouse is inventory the same way that a part on the assembly line is. However, parts in the warehouse do not take up building space. When an incomplete set of parts is released onto assembly, only a certain number of steps will be feasible before having to stop for lack of parts. If this is the case, the partial build will be taking up space on the assembly floor and will be there until the remaining parts arrive. Different release policies were observed at the sites included in the study.

Ten days before a build is due to start at site A, information about the parts that will go into that engine is made available to the crew leader via the MRP system. At that time it is known which parts should arrive on time. Three days before the scheduled start date, it can be seen whether the parts actually made it to the plant. At this point, an assembly leader can use his expediting resources to get these parts to the factory floor on time. Assembly leaders would probably not be interested in having a greater than three days window in this matter, since they would already be busy trying to get parts for their other engines due to begin assembly. Also at site A, incomplete sets of parts are authorized for release to the assembly floor. The theory behind this policy is that any steps that can be performed on a build will help to finish the engine sooner. When a step in the build is reached where work cannot continue, a so called work-around' will be performed. In most cases the implementation of these work-arounds will require a lot of attention from the cell leader. This is because every work-around is unique and non-standard by definition; non-standard work adds to cycle time. We were not able to collect data that would explain quantitatively the effect of work-arounds on throughput time, but our observations supported the fact that work-arounds contributed to increment throughput time rather than decrease it.

At site B, work-arounds are not performed, but parts are also released onto the floor in partial sets when not all of them are available. Here the foreman in charge of the build area will decide which engine he will have his people working on, based on the parts he has available that day. This system, as the one in site A, would appear to be based on the idea that as long as operations are being performed, value is being added to the products. The policies in these sites are to keep the people busy building engines; any engines.

However, at site C this is not the case. A build is not started until all the parts required are available. Only in rare cases does the assembly leader, the only person authorized to make such exceptions, authorize the begin of builds with less than 100% of the parts available. At this site the policy is to build according to the production plan. If people are not busy at a particular moment, they do not start other builds. They wait to perform the next steps on the scheduled builds when they are required.

4 Data Analysis

Six particular engine models were analyzed during this study. Although similar in principle, these engines were quite different from each other in some important aspects as thrust, weight and part count. A common base line had to be established to begin to compare the engines, and their production systems.

Number of Parts vs. Planned Build Time

As seen in table 1, there would appear to be a relationship between the total number of parts in an engine and the days allotted to the build. These numbers are plotted in figure 13. The resulting R^2 value is high enough to suggest that there is a strong correlation between these values. Hence, if needed, this correlation could be used to normalize time data between different engines.

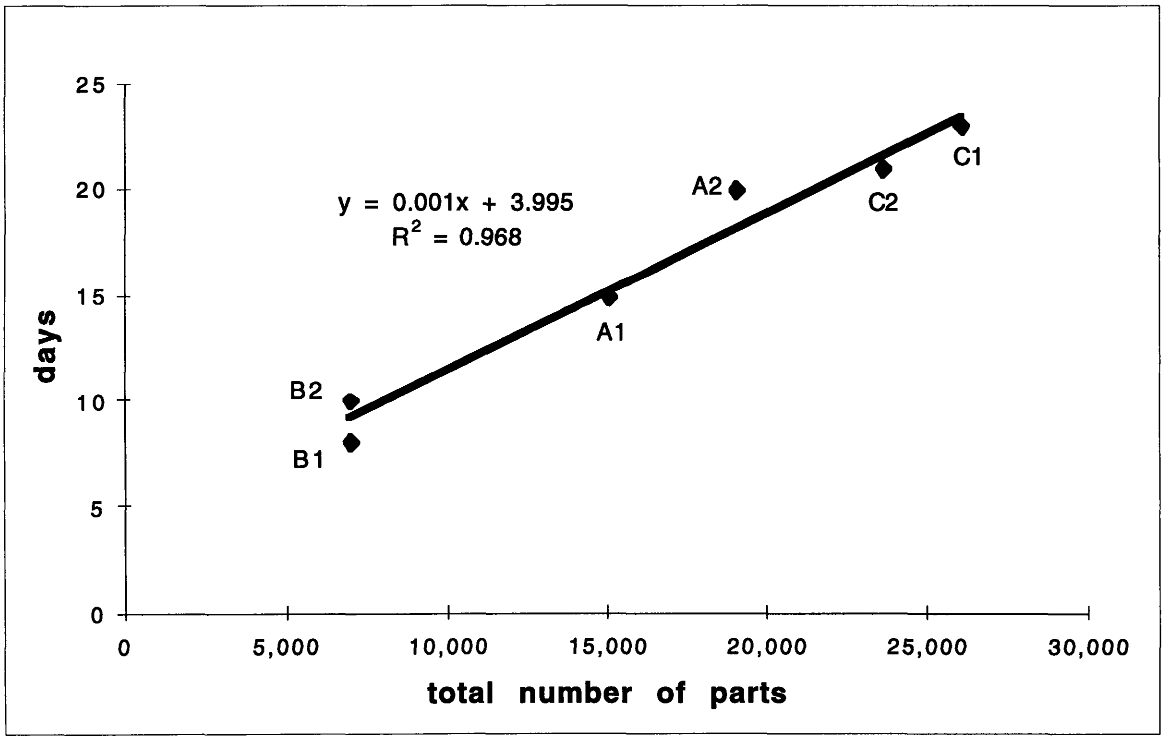


Figure 13 - relationship between total piece count and planned build time

It seems that planners in different companies use the same general approach to estimating build time. In figure 13, the letter identifying an engine indicates the site where it is built and the number serves to distinguish between the two models analyzed; 1 for military, 2 for commercial. The figure also shows that there seems to be a approximate rule of allowing a day for every 1000 parts in the build. The operations to make these engines must be roughly similar.

Actual Build Times

It is one thing to plan to take a certain amount of time to build an engine. It is another to actually build it during that time and it is yet another to do so repeatedly. During this study (the observation period for individual sites was not shorter than 3 months and not longer than 6 months) the actual build times for engines analyzed were recorded. Figure 14 shows the same data as figure 13, however, it also shows the actual build times that the particular engines take to build.

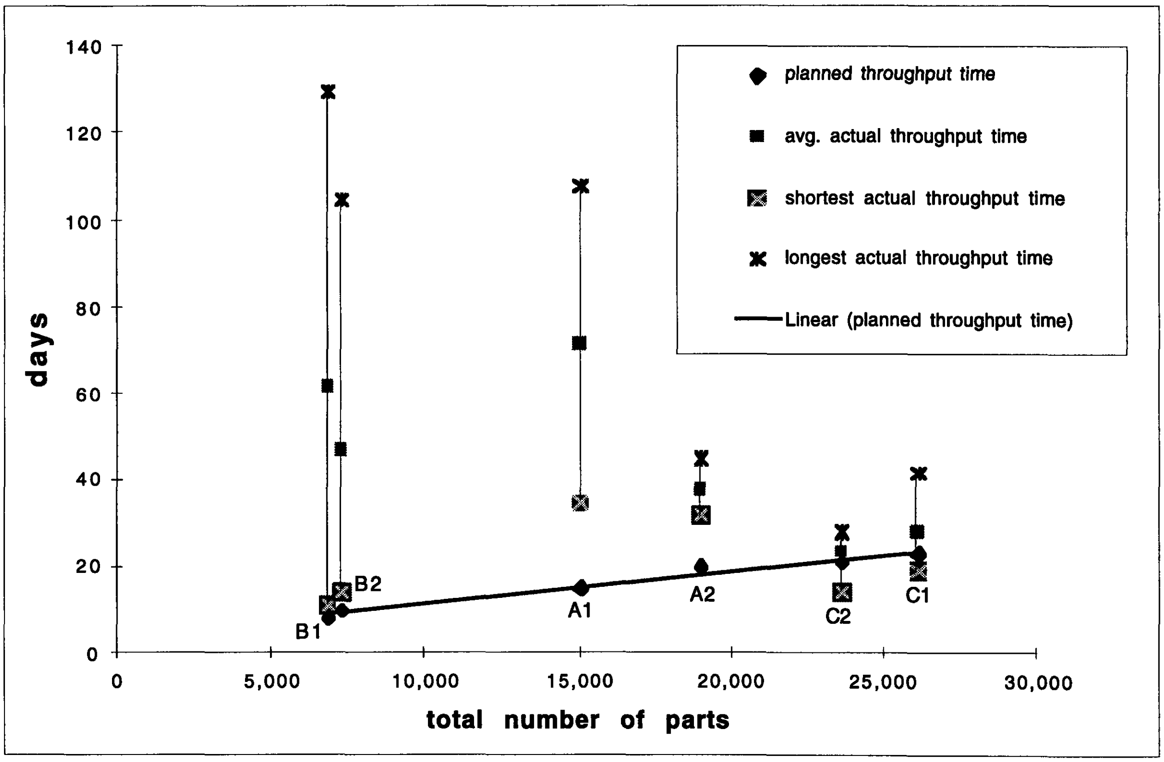


Figure 14 - actual averages and ranges of build times

It can be seen that engines A1, B1 and B2 take in average approximately four times longer to build than initially planned. Engine A2 takes about twice the time allotted. However, the engines at site C are very near their target build times, taking in average only between 10% and 20% longer than the planned build time. Figure 15 shows the average delay per engine, the difference between the actual average and the planned throughput time. The difference between the lateness of engines at site C and the other sites was approximately one order of magnitude. The closest engine, A2, had an average delay 4 times greater than C1 and C2 combined.

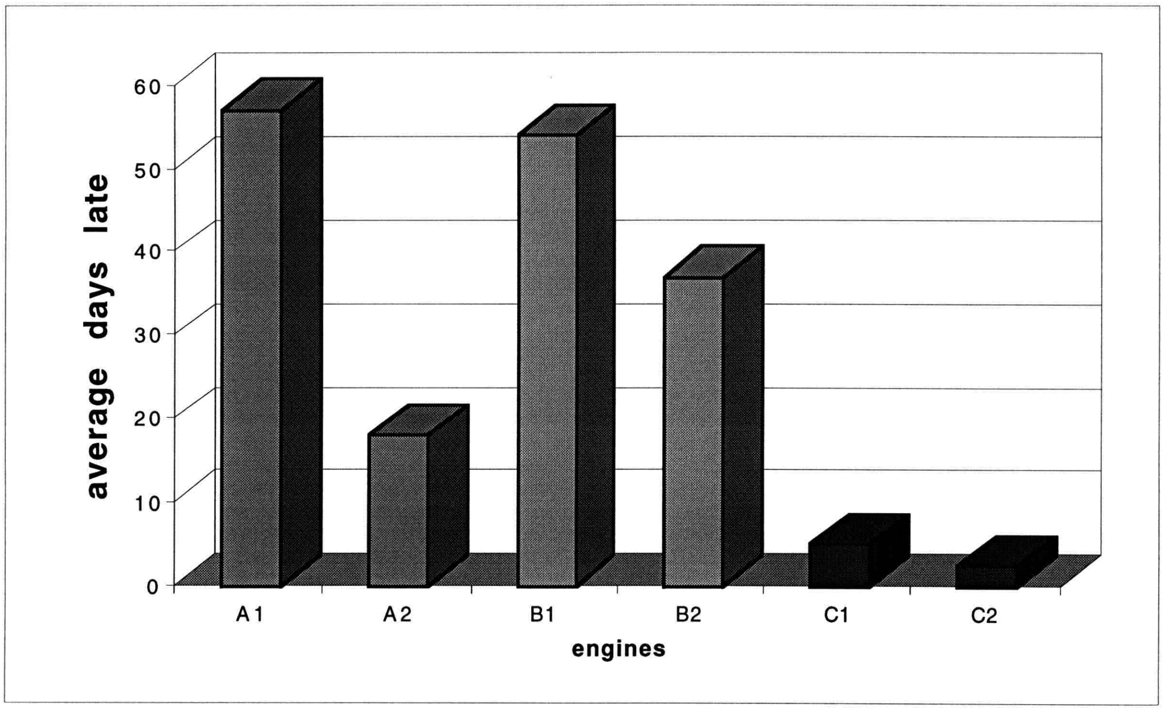


Figure 15 - average difference between planned and actual throughput times

It would appear that the production system in site C somehow manages to keep the build times under control and relatively on schedule, even though their engines have the largest number of parts of the sampled models. Note that if the delay data is normalized by the number of parts (see figure 16), as previously justified, the differences between the C engines and the A and B engines is even greater. The value for engines A1 and B1 are the highest, followed by B2.

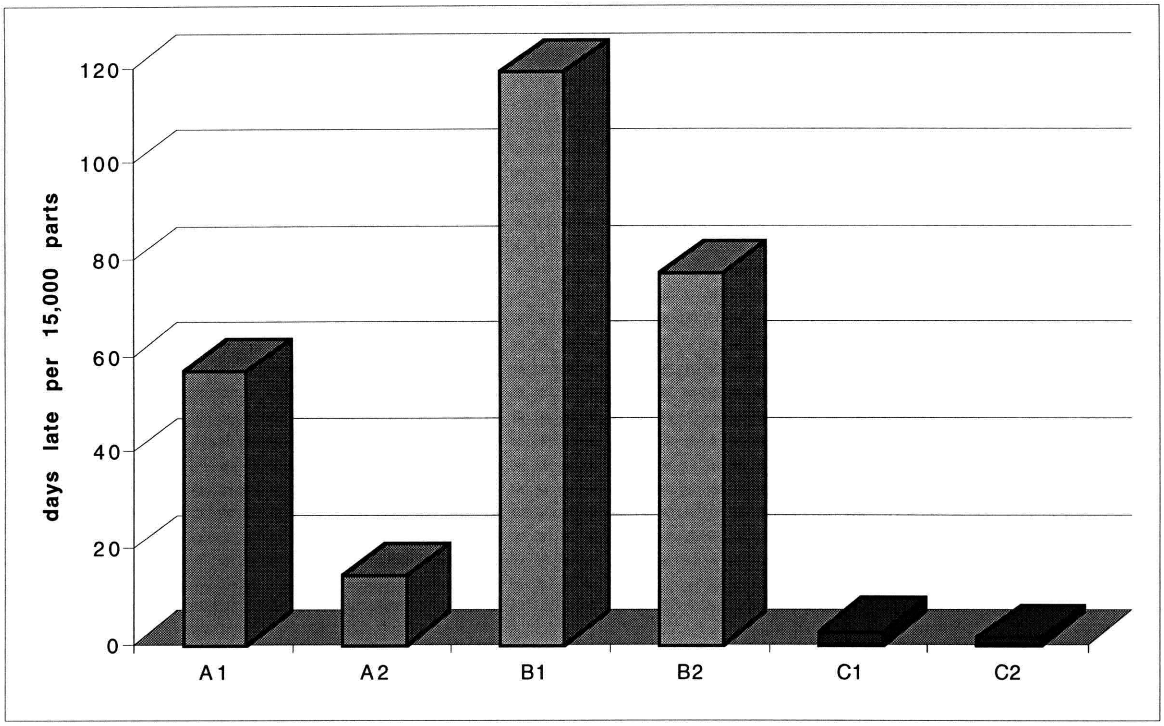


Figure 16 - average lateness normalized (divided) for 15,000 parts

The values in figure 16 are the days it would take each of these sites, in average, to build an engine with 15,000 parts based on the data collected.

Build Delays

Build delay problems can be of several types. For this study, the following categories were defined into which all delays would be broken down:

- Part shortages
- Part lost on-site
- Quality problems
- Build awaiting inspection
- People availability
- Tooling availability
- Station availability

At each site, available engine build records were analyzed and the build spans and sources of delays for as many engines as possible were tracked (7 engines at site A, 8 at site B, and 8 at site C). In every case the record keeping system was different. At site C, exact records were kept of when a build was begun, finished, and what if any perturbations had occurred during the build and for how long they had existed. At site A, engine assemblies and delays were documented, but did not always include all the reasons for delays or an accurate record of the duration of the delays. Engine files at site B indicated when a build had started and when it had ended, but no mention was made of what had caused those engines to be delayed.

Knowing and understanding the problem is half the solution. Workers and engineers at these sites were very good at tackling problems once they knew what the problems were. However, we found that in many cases their efforts were hindered by a deficient system that could not track problems and record them.

From the management perspective, actual root cause data collection did not appear to be their highest priority in some instances. They were interested in knowing what their conformance to MRP schedule was, or how many engines during a month they would be able to produce. Hence, the impact this had on the system was that everyone else was also interested in performing well according to those measures, whether they were good for the system or not.

Site A

Figure 17 is the breakdown of the reasons for delays in engine type A1, a military unit. These delays, as well as those discussed later for engine A2, were on the critical path of the engine assembly and therefore stopped the build completely. In the other sites it was not possible to determine whether the delays had stalled the engine build or not.

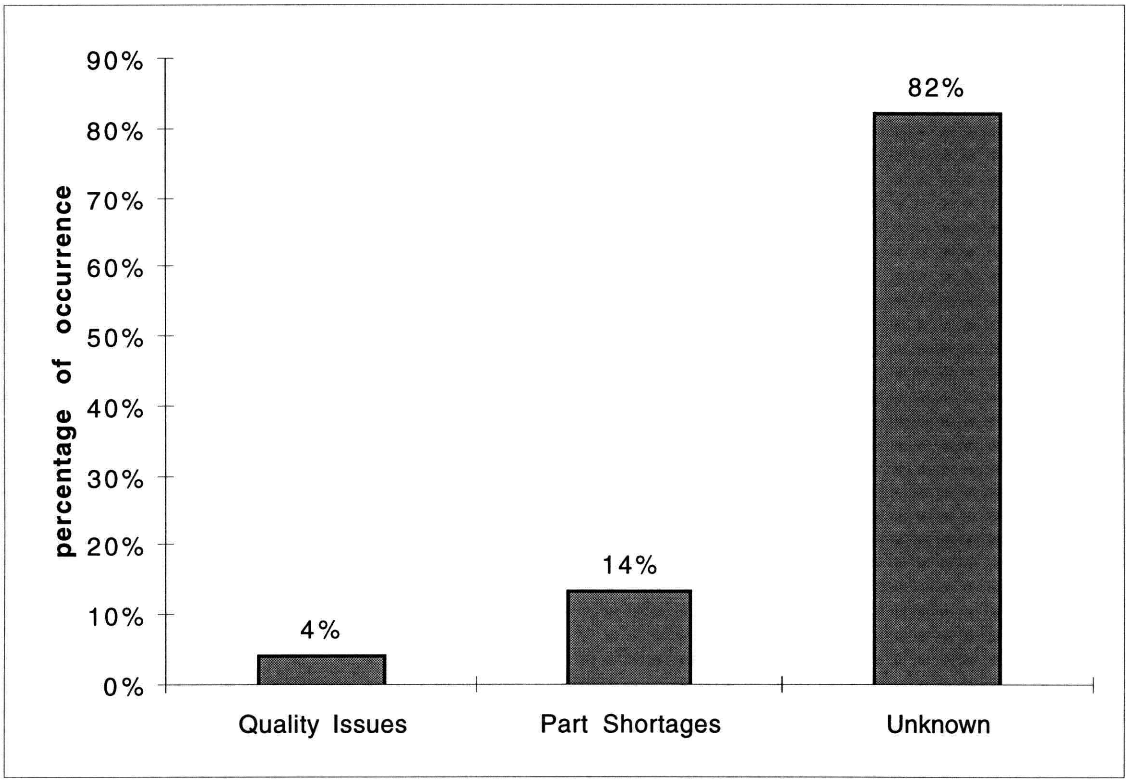


Figure 17 - Reasons for delays, engine A1 - military

By far the greatest portion of delays couldn't be traced. This chart is based on engines that were built over the duration of the study at the site (from 1 to 2 months, depending on the site). Although build records were reviewed and people involved in the build were interviewed, it was not possible to determine what had caused 82% of the delays. Operators and foremen were most willing to help, but there wasn't a way to accurately determine what had caused all delays. In the case of engine A2, a commercial model, the results were similar, as show in figure 18.

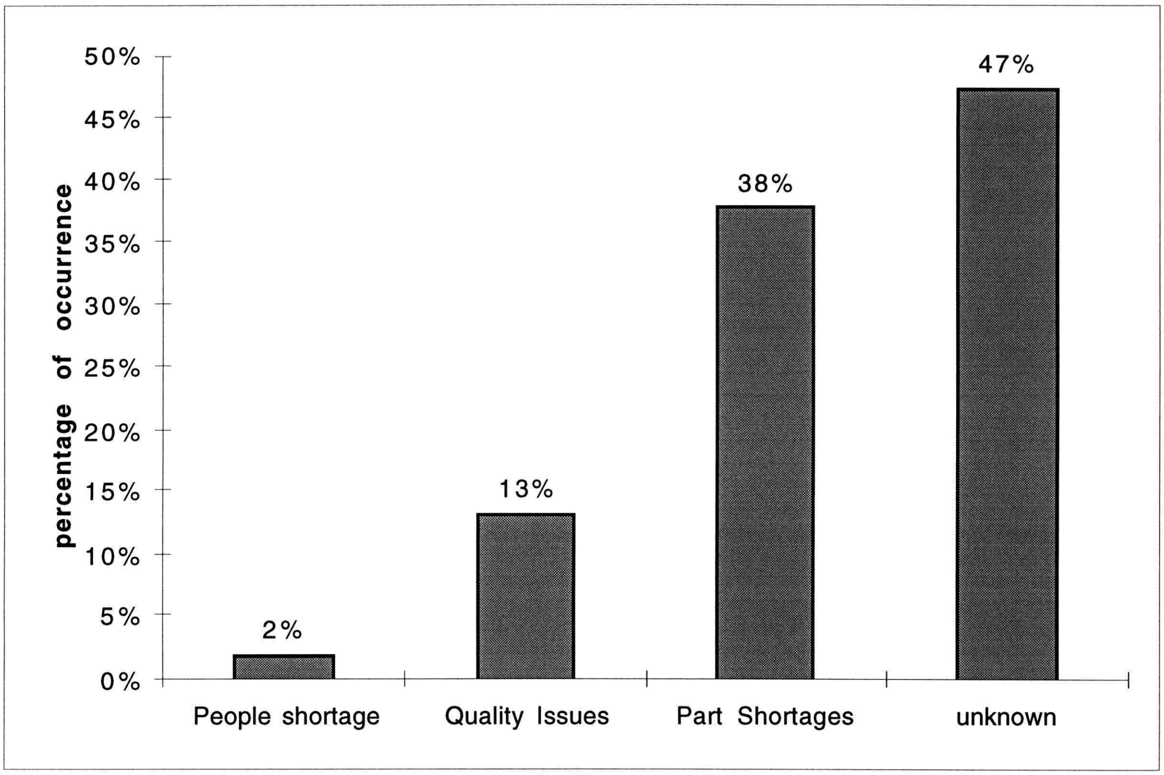


Figure 18 - Reasons for delays, engine A2 - commercial

Of those delays that could be identified, the majority were caused by part shortages. The second most important cause of delays identified were quality problems. These include parts that seem to be damaged and require to be evaluated, parts that don't fit, and upstream steps that need to be re-checked because they appear to be deficient.

Site B

In site B no records were kept of reasons for delays. Hence, the information given here was gathered through interviews with assembly leaders and foremen and through the tracking of 8 builds over the duration of the study (1 month) at the site. This tracking was done by asking the foreman in charge of the build, to keep a sheet were he recorded the start and end of the build as well as any perturbation that had occurred during the build. They were asked to record the duration and nature of these problems. Figure 19 shows the average of the responses based on the six interviews conducted. The averages attributed by the interviewees were very similar.

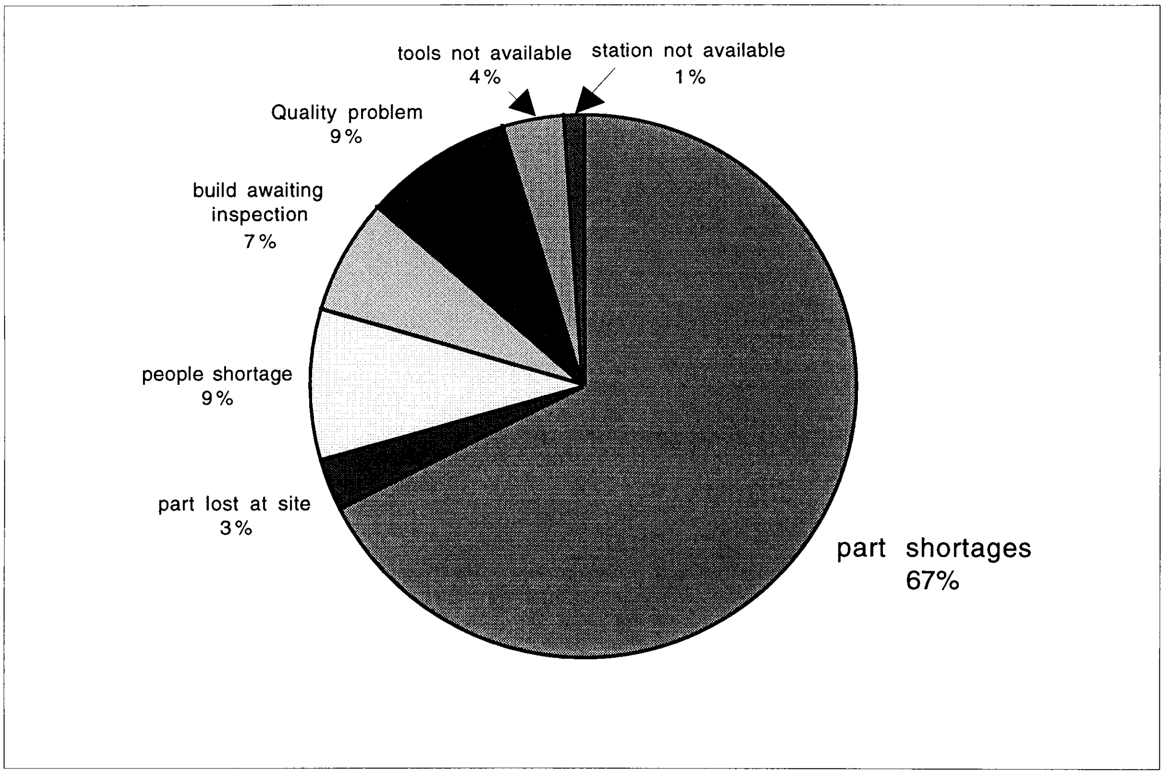


Figure 19 - averages of responses for reasons of delays at site B

The tracked builds included the final assembly of 2 B1 units (final stacking only), 2 B2 units (again, final stacking only). and the complete assembly of 4 units of a third type (B3) of engines made at the plant. Compressor and Turbine assembly data could not be tracked for the B1 and B2 engines. 5 of the instances where delays were experienced were caused by part shortages and 2 by quality problems. Between this data and the result of the interviews, one could again argue that the main source of problems for the assembly stage of an engine build was the unavailability of parts. Also, as seen in the previous site, shortages due to quality were in second place. The result of the data collection done by the foremen is shown in figure 20. The data for each is shown by two points (one for start date and one for finish date) and a label for the type of perturbations, if any, that occurred.

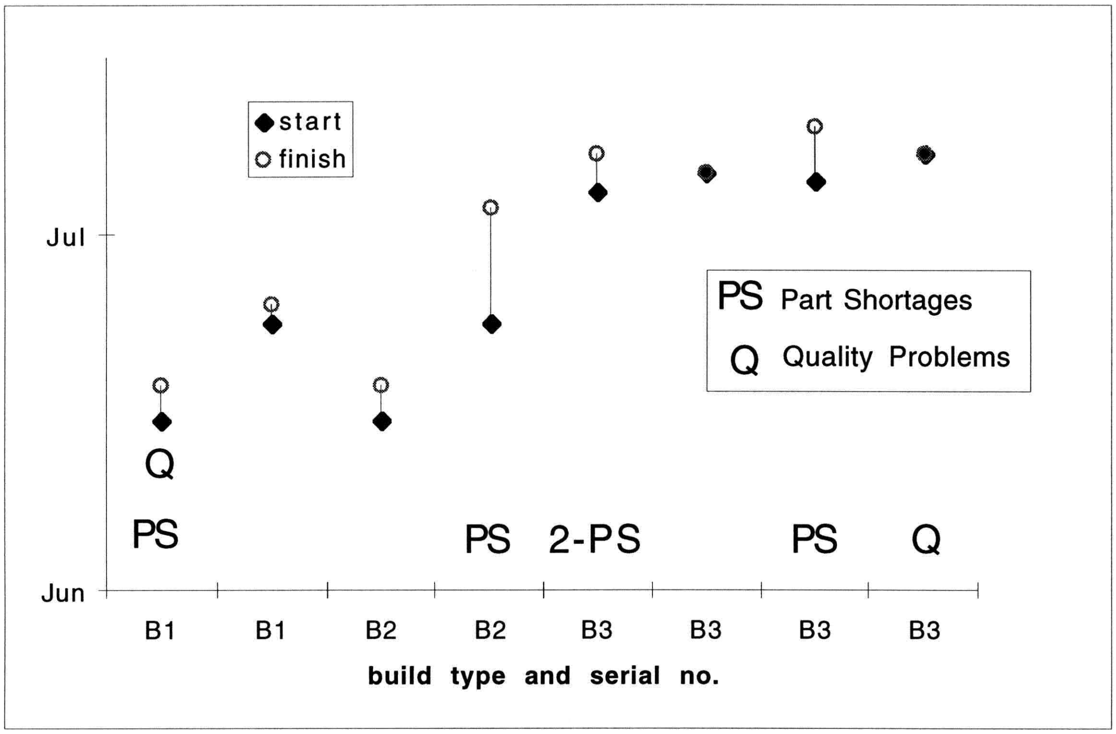


Figure 20 - build spans and perturbations for engines tracked at site B

Site C

The records kept at site C were the most complete. For each perturbation that an engine experiences during the build, an entry is made that includes a description of the problem, time when it occurred, steps taken to solve it and time when the problem was solved. Figure 21 shows the frequency of occurrence of reasons for delays in engine model C1.

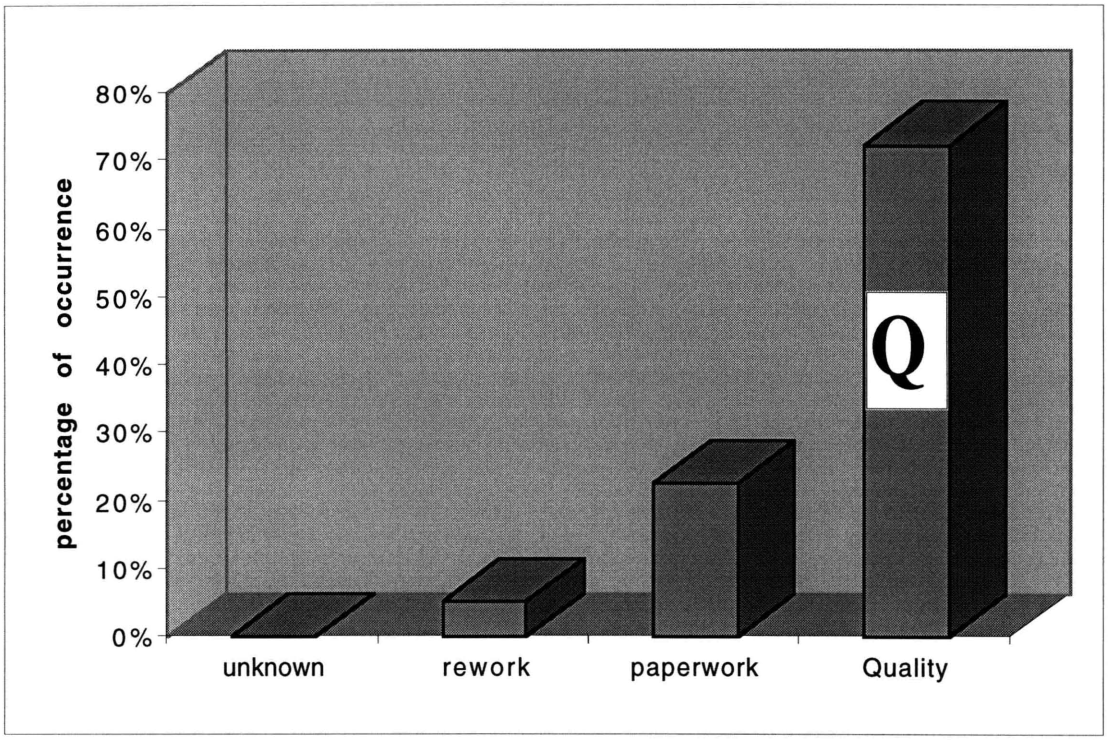


Figure 21 - reasons for delays in 4 sampled C1 engines

At this site data was not only recorded properly, it was also very easily accessible. Again, we did not find any site where participants were reluctant to help. On the contrary, this study would not have been possible were it not for the help of the engineers, foremen, administrators and operators at the sites included. However, at site C, information was always available within a few minutes of being requested. This reflected a discipline in record keeping and information availability, both of which are vital to a production system. Figure 22 contains the data corresponding to engine model C2. Of each of the engine models at site C, 4 individual serial numbers were evaluated more deeply to obtain these figures. It could not be determined during the study whether these delays were in the critical path of the engine, thus it is possible that these delays did not cause the engine assembly as a whole to be delayed. They were just perturbations that did not impact the engine throughput time.

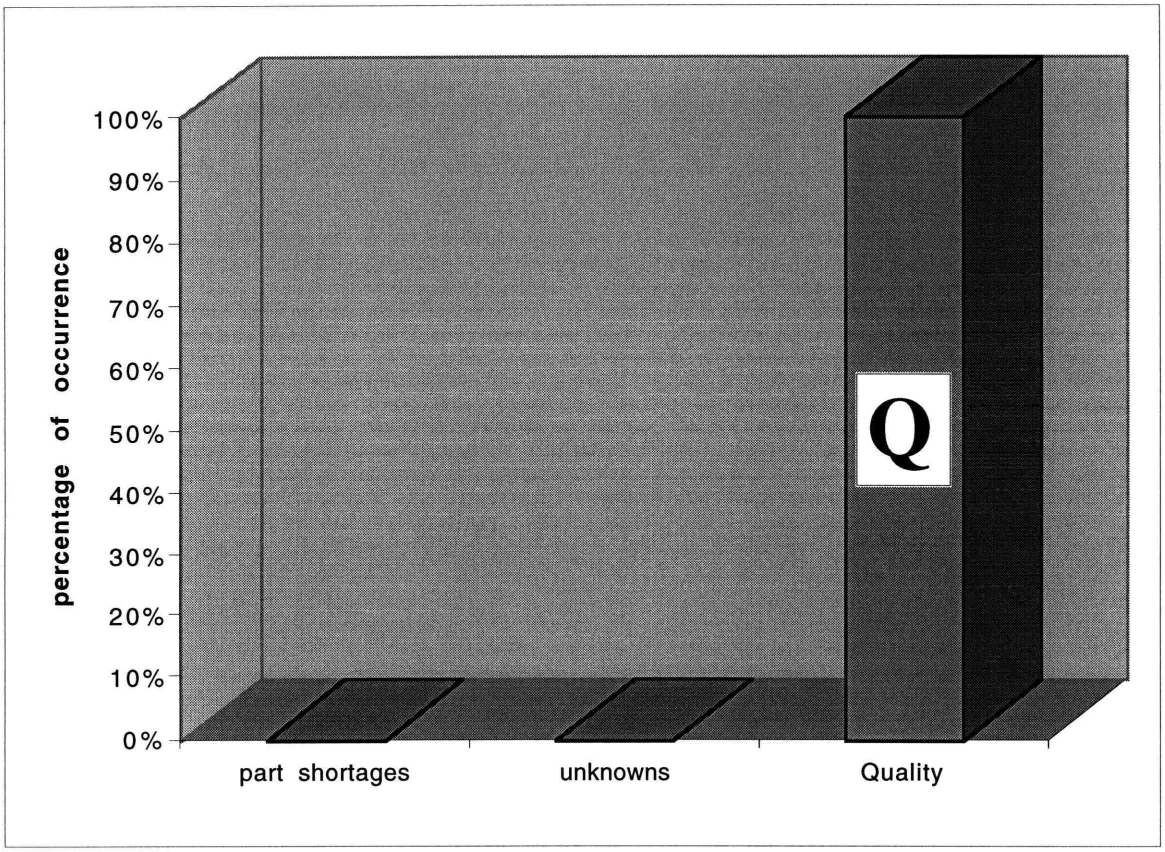


Figure 22 - reasons for delays in 4 sampled C2 engines

As we saw earlier at sites A and B, part shortages play a major role in delaying builds. At site C, however, no single instance of part shortages was found during the span of this study. The quality problems experienced at these sites were quite similar between each other. After all, the supplier base for the aircraft engine industry is not very wide. Some parts are only made by one or two suppliers in the world, thus these sites get their parts from the same suppliers in many cases. Site C has different agreements with suppliers than do sites A and B. Suppliers at site C are kept informed of the status of builds and the actual requirements of the assembly floor. The suppliers know when they have to deliver exactly which parts to the factory.

Assembly methods are not that different among the sites. One could argue that site C has far more time to devote to solving problems such as quality, or station distribution, while sites A and B barely can worry about these seemingly secondary issues, since their biggest problem by far is the shortage of parts on the floor. Site C is one step ahead on the road to lean, since it has made significant progress in eliminating part shortages and can now focus on improving other aspects of its production system which still have room for improvement.

On-time Deliveries

A customer not only wants a product to have excellent quality, reliability and a low price. The product must also be available on time. Perhaps the most important performance measure evaluated during this study was the frequency of on-time delivery.

At site B, on-time deliveries are not very often. Figure 23 shows the breakdown of on-time and late engines of three types at site C. This is based on data collected at the site by an improvement team covering over 600 engine builds).

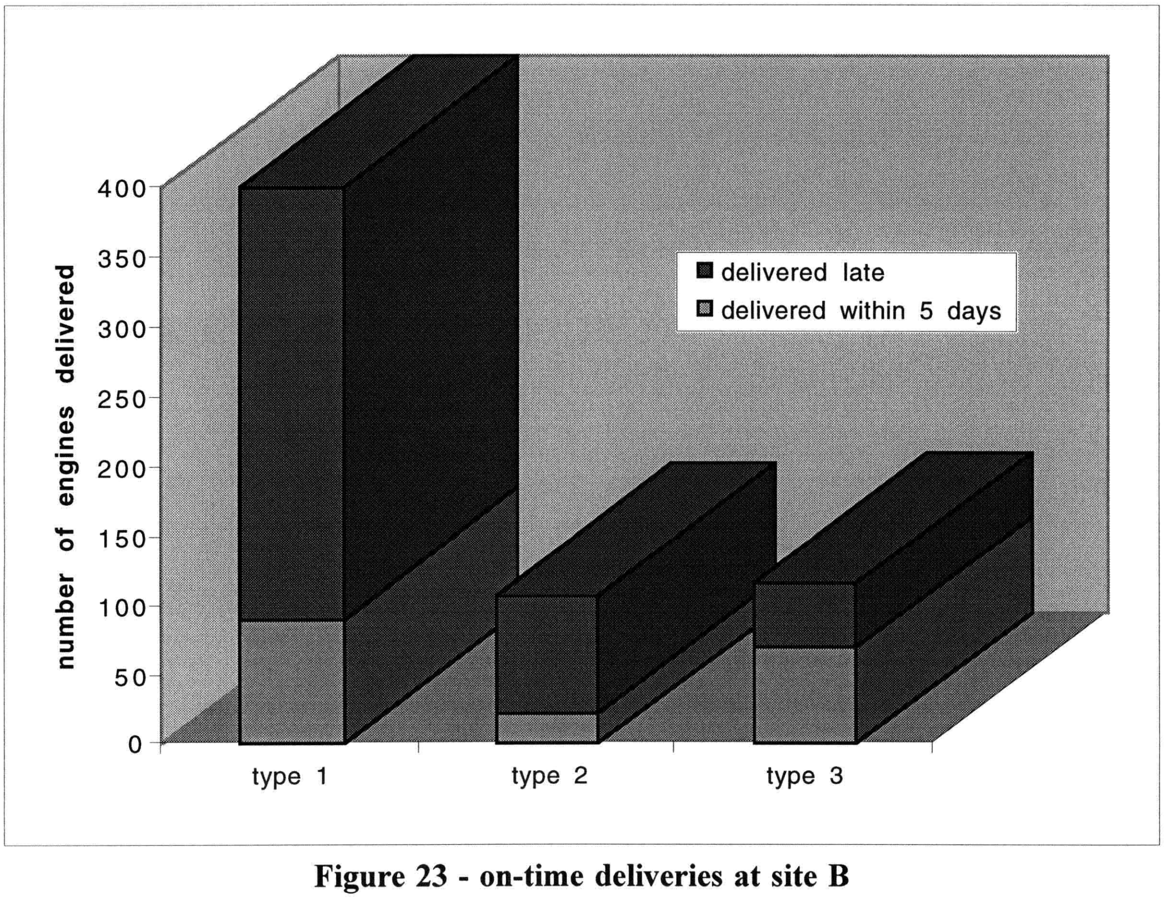


Figure 23 - on-time deliveries at site B

At site A; approximately 67% of the engines were delivered within contract dates during the period of observation (3 months). At site C, no late deliveries were made during the study (2 months). Figure 24 shows the percentages of on-time deliveries for sites A, B and C.

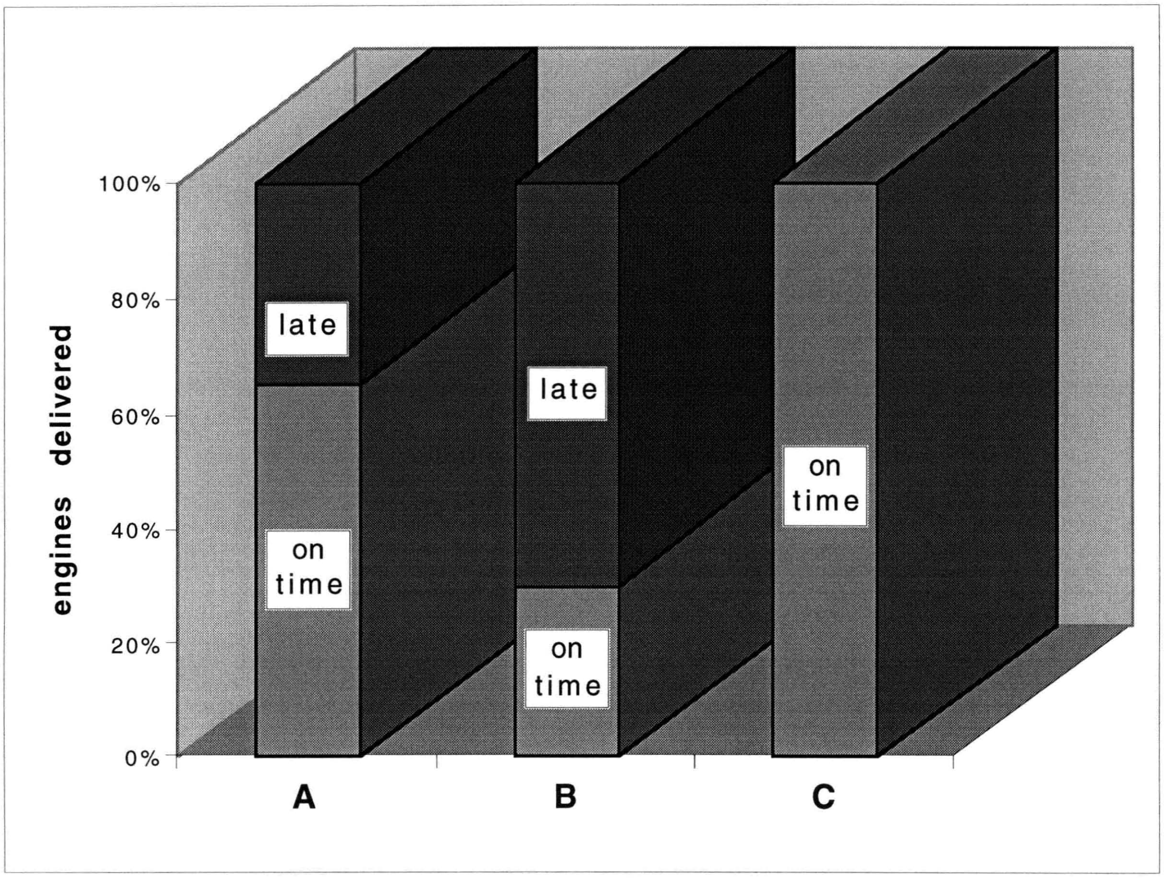


Figure 24 - on-time deliveries at sites A and C

We also looked at the rate of deliveries. All other things being equal, a production system that has a relatively constant level of operation, and thus deliveries, has the ability to operate better than one in which production goes through pronounced cycles. Figure 25 shows the deliveries made by site B during a 3 month period while figure 26 shows deliveries at site C for the same period.

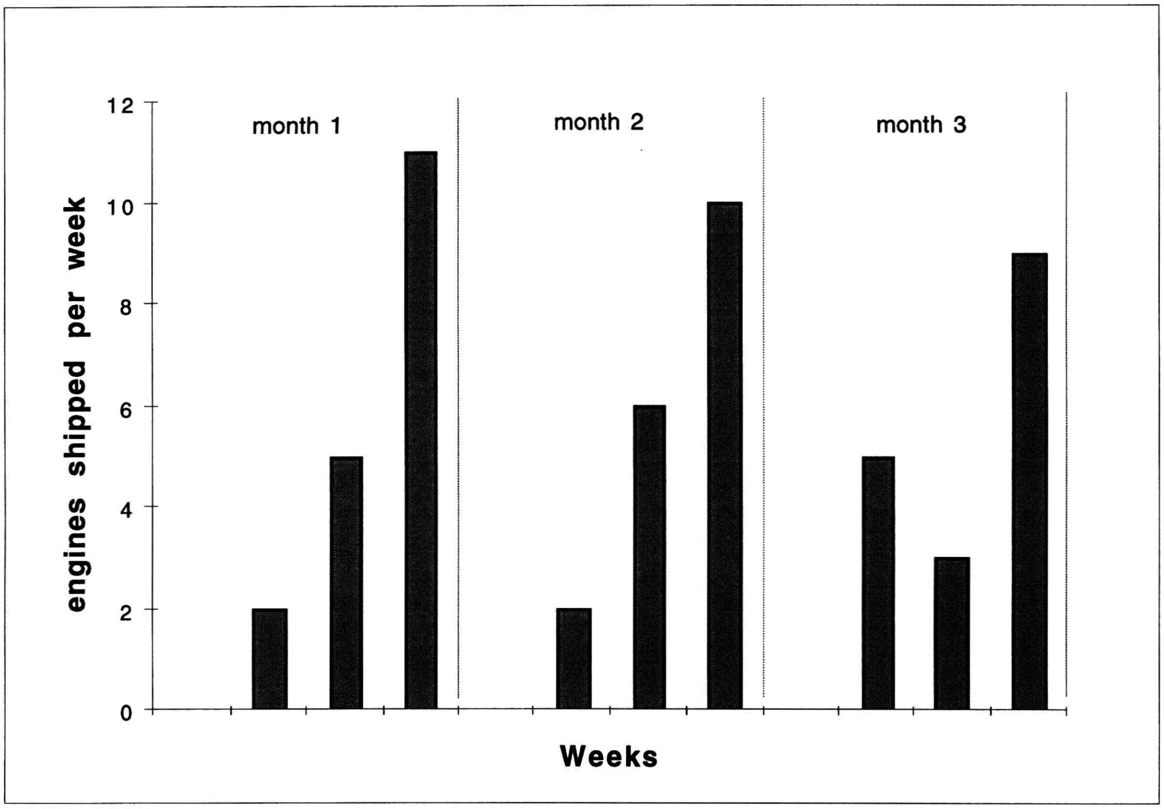


Figure 25 - engine deliveries at site B over 3 months

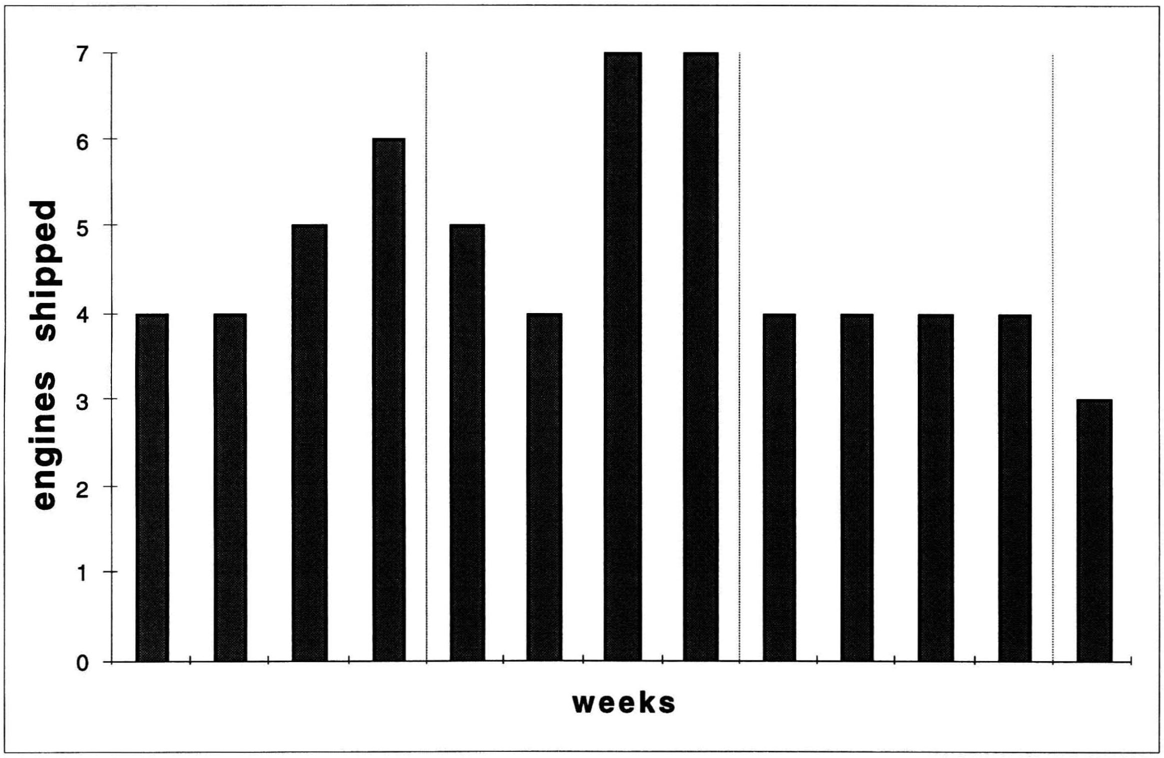


Figure 26 - engine deliveries at site C over 3 months

In general, these two patterns represent the nature of the production system as well as the incentive structure used at the factory. The pattern seen in figure 25 is typical of batch made job shops which need to meet monthly targets. Figure 26, on the other hand, generally reflects a factory that uses level scheduling.

In a leveled schedule, production is held constant over a period of time. During that period, the workforce is kept constant and inventory low; the system depends on demand to pull products through. Level production has the advantage that product modifications are up to date due to the low level of inventory and work in process. There is also a steady flow throughout the production system, which enables parts from suppliers to be delivered when needed. The mix of parts is also spread out, so that having to deliver a concentrated number of parts of one kind at any particular time happens only rarely.

Changes in Layout

After the data collection at site A had been finished, the floor was rearranged. The common build areas for modules as had existed when the study had begun, had been replaced with dedicated engine lines. Within these lines, smaller areas, about one fifth the size of the previous ones, existed for the build of sub-assemblies within the lines. A second data gathering trip was made to analyze some aspects of this new layout.

Throughput Time and Performance to Schedule

During this visit, data was gathered on the actual throughput time of engines and their lateness to schedule. The data covered 20 A1 engines and 21 A2 models. Figure 27 shows the increment in throughput time, or the difference between the actual and the planned throughput times, for the A1 engines. It also shows, on the left, the corresponding range and average values that were recorded during the first visit to the site (data contained in figure 14) as a reference. The significance of the period sampled is that during the summer, the layout changeover began and was completed during November. One could expect to see a gradual improvement if the new layout was going to yield better performance in terms of the assembly of engines. The trend seen in figure 27 suggests that such an improvement was taking place. The net improvement is a roughly one order of magnitude smaller increase in throughput time. In figure 28 the data is presented as a range including the average and a comparison to before the layout at the same site and the performance of the production of engine C1, also a military model.

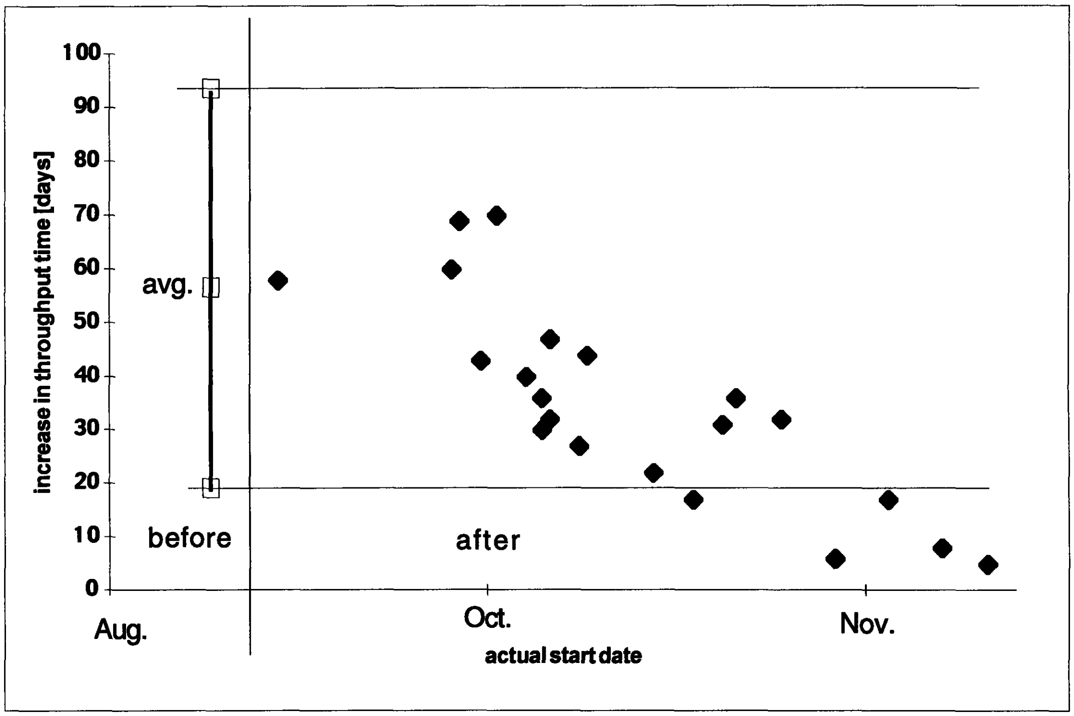


Figure 27 - difference in planned vs. actual throughput times, A1 engine

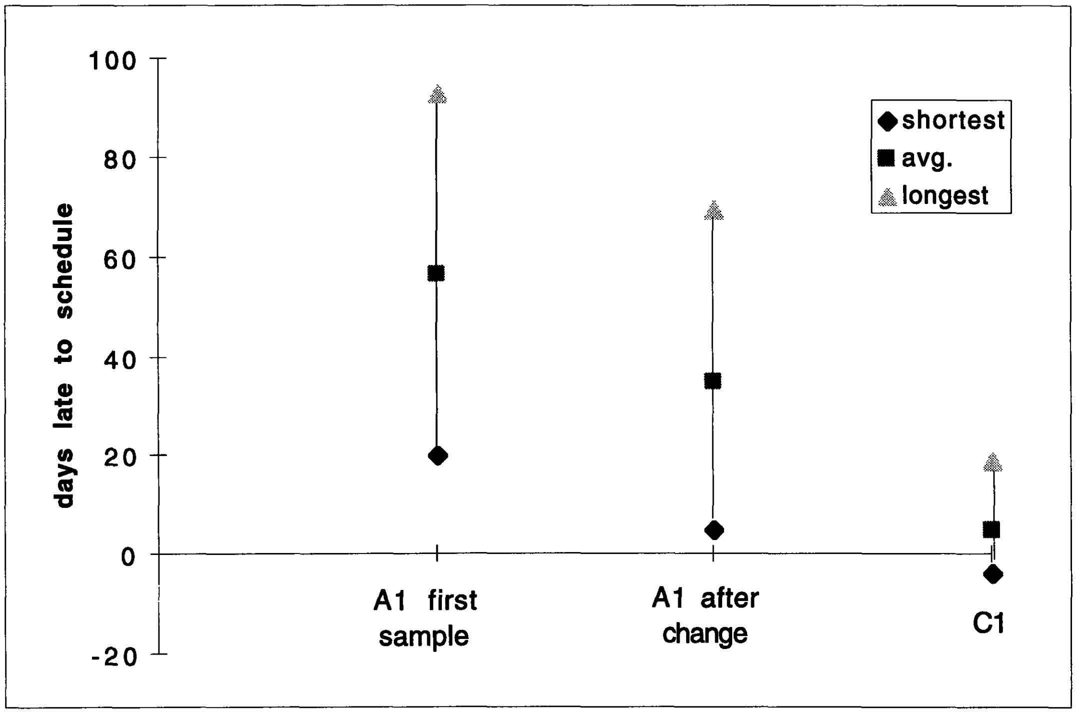


Figure 28 - performance of A1 production before and after layout change

In the case of the A2 engines, the beginning of the layout changeover didn't take place until the Fall and had not been completed by the end of the year. Up until the layout began to be changed (marked as transition in figure 29), there is no clear trend of reduction in the increase in throughput time. However, after that point, a steady decrease can be observed.

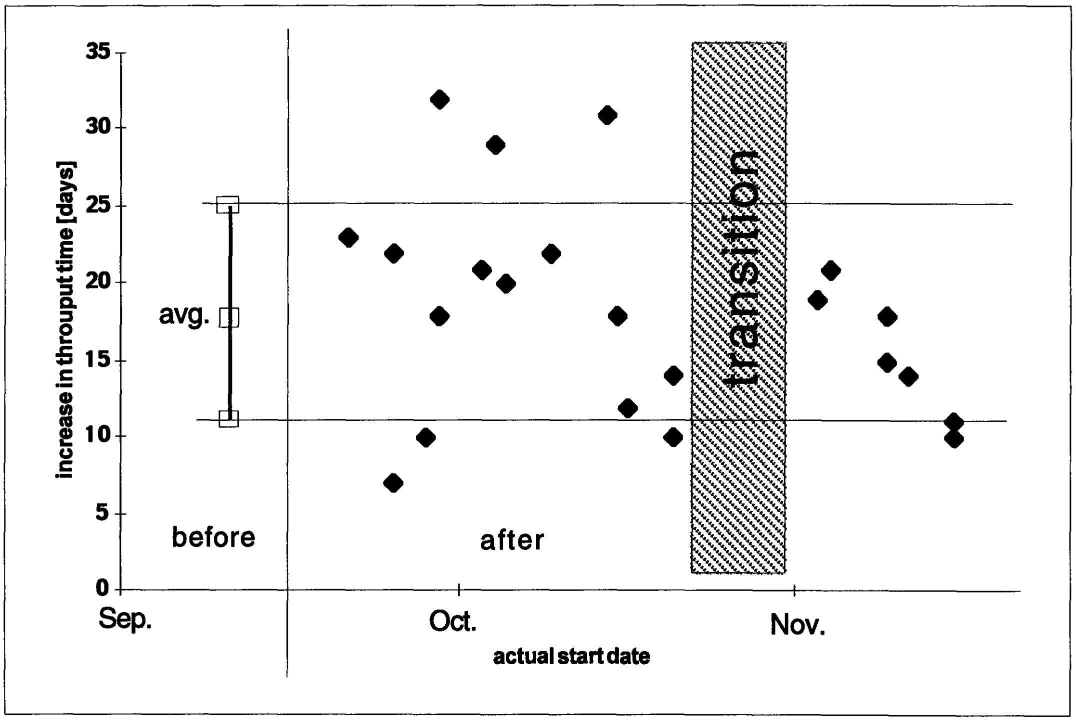


Figure 29 - difference in planned vs. actual throughput times, A2 engine

In figure 30 the same data as that shown in figure 28 is plotted, only this corresponds to the A2 engine. In this case not only the reference from the first sampled engines is presented, but also that of the engines produced immediately before the change in layout was started. As in the previous case, a comparison with the equivalent C site model, the C2 engine, is presented.

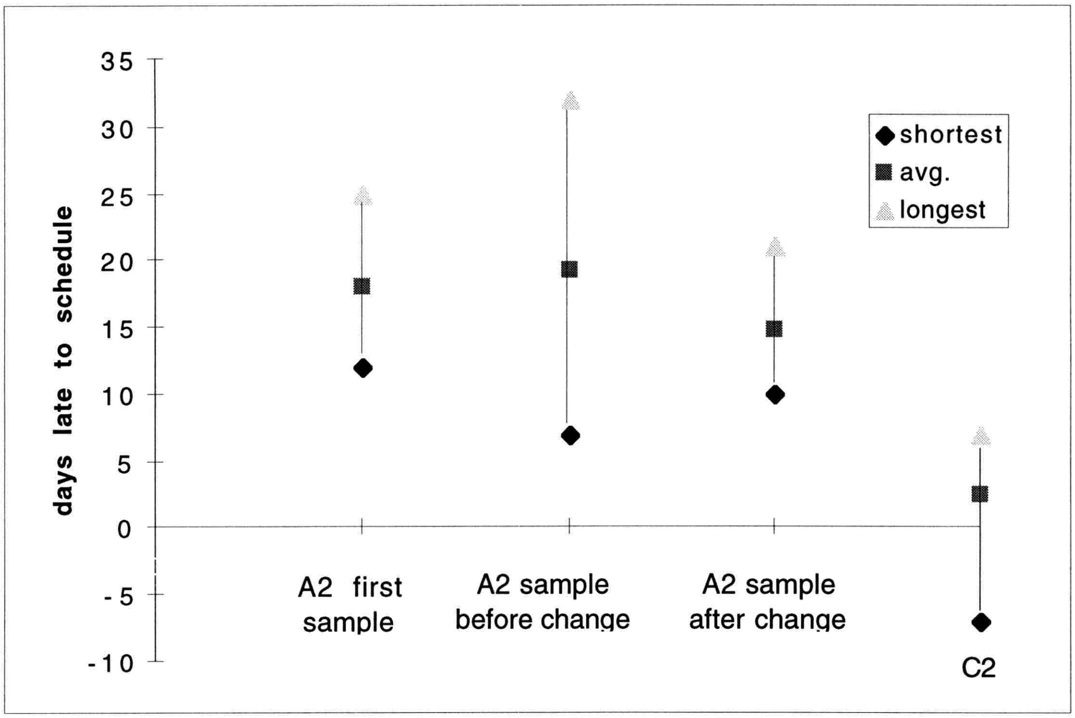


Figure 30 - performance of A2 production before and after layout change

Another performance measure analyzed over the span of this study was the conformance to scheduled finish date. A similar trend to that observed in the increase in throughput time was also found in the performance to schedule of the builds. Figure 29 includes data points for A1 engines.

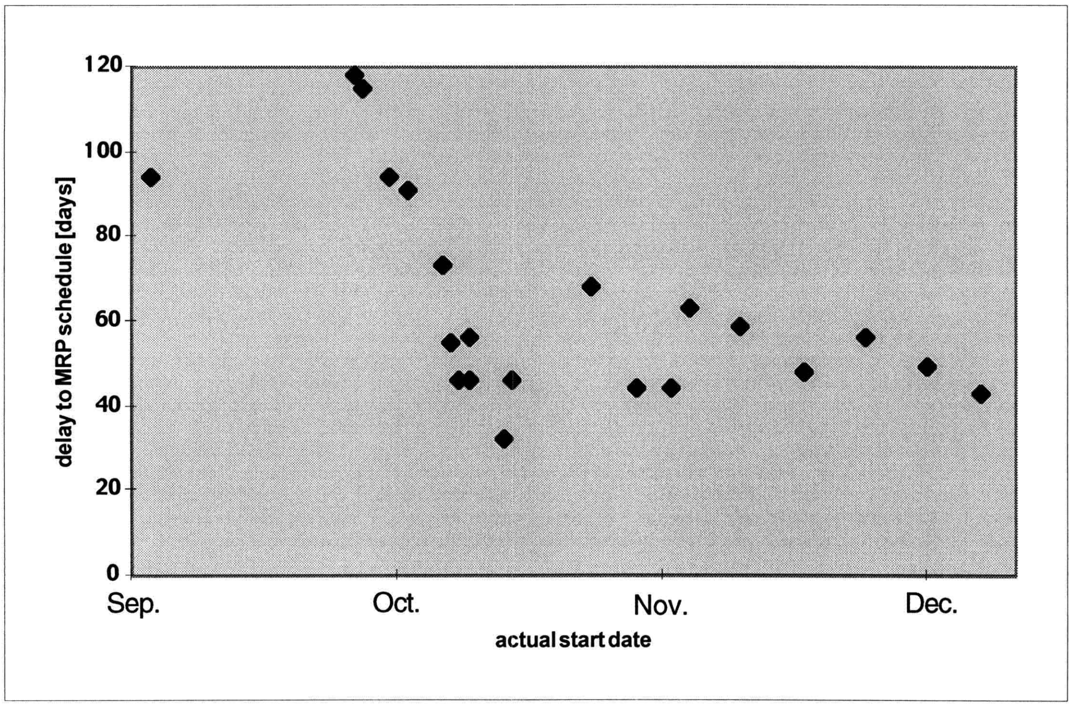


Figure 31 - performance to schedule, A1 engines

Similarly, there is not a clear trend in the conformance to schedule in the A2 engines before the layout began to change. Nevertheless, a trend does appear to exist after that time. Figure 30 shows the delay to schedule as a function of actual start date for A2 engines covered in this part of the study.

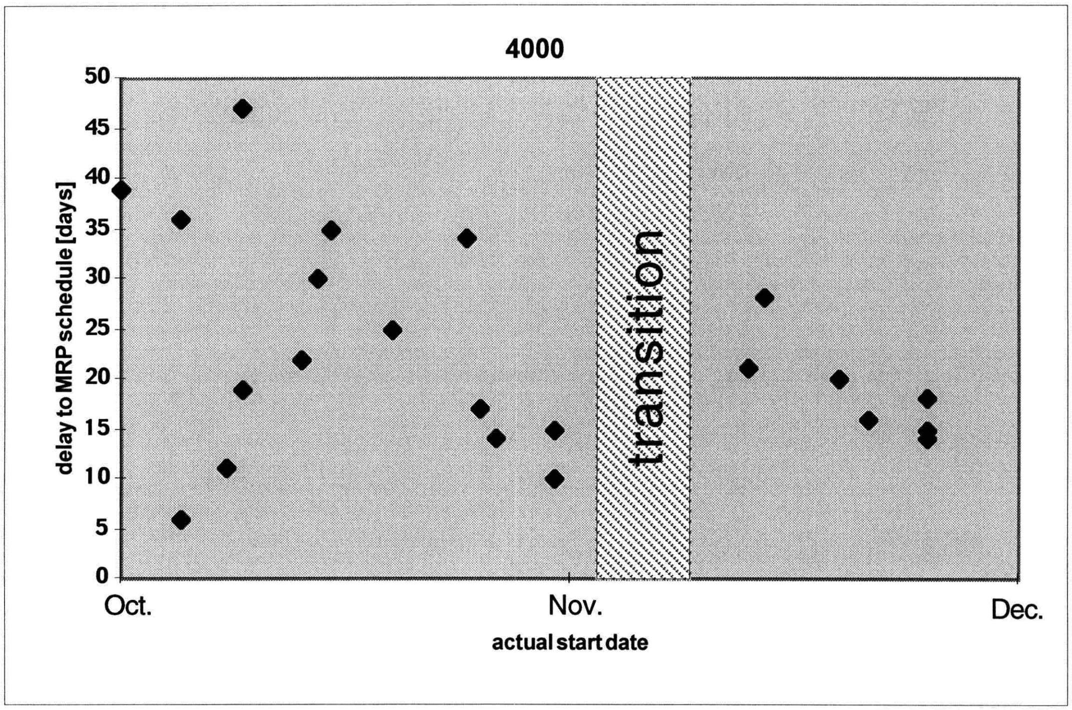


Figure 32 - performance to schedule, A2 engines

Reasons for Delays

As in the previous part of this study, the reasons for delays in the builds were also analyzed. Build records for 5 A1 engines were examined as well as for 4 A2 engines. In this case, as in the data analyzed at sites B and C, delays were not identified as being in the critical path or not. Thus, these delays might have stalled the engine build or not. However, they are delays that occurred during the build. Figures 31 and 32 show the frequency of occurrence of delays for A1 and A2 engines respectively.

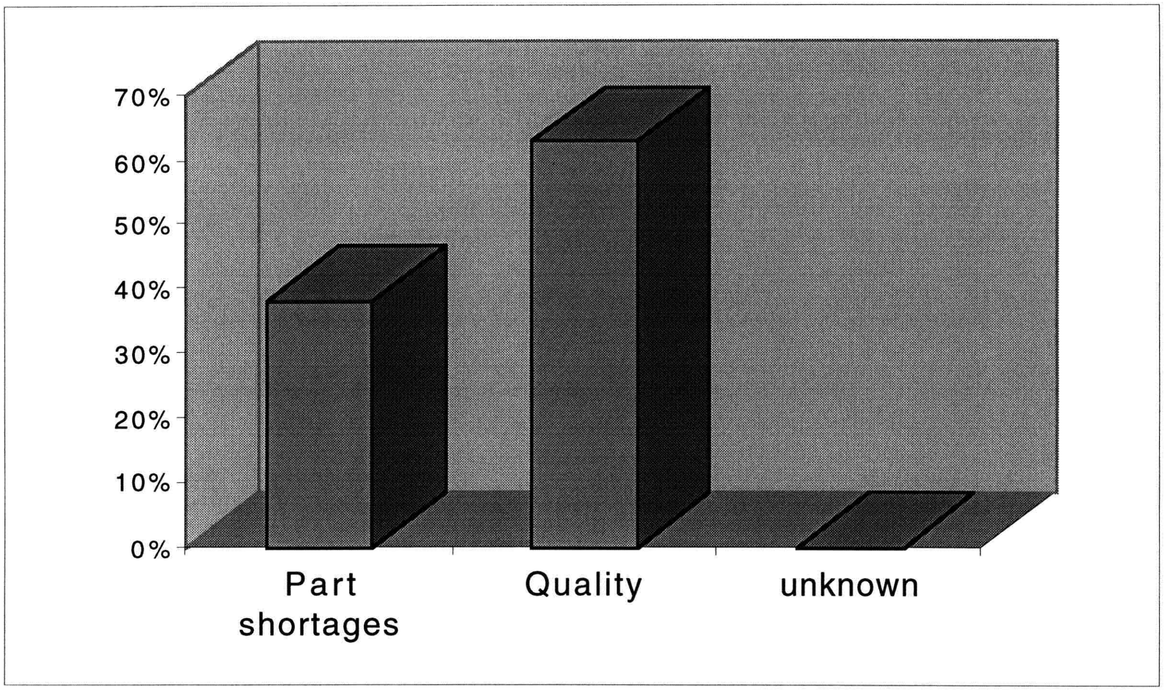


Figure 33 - reasons for delays in 5 A1 serial numbers

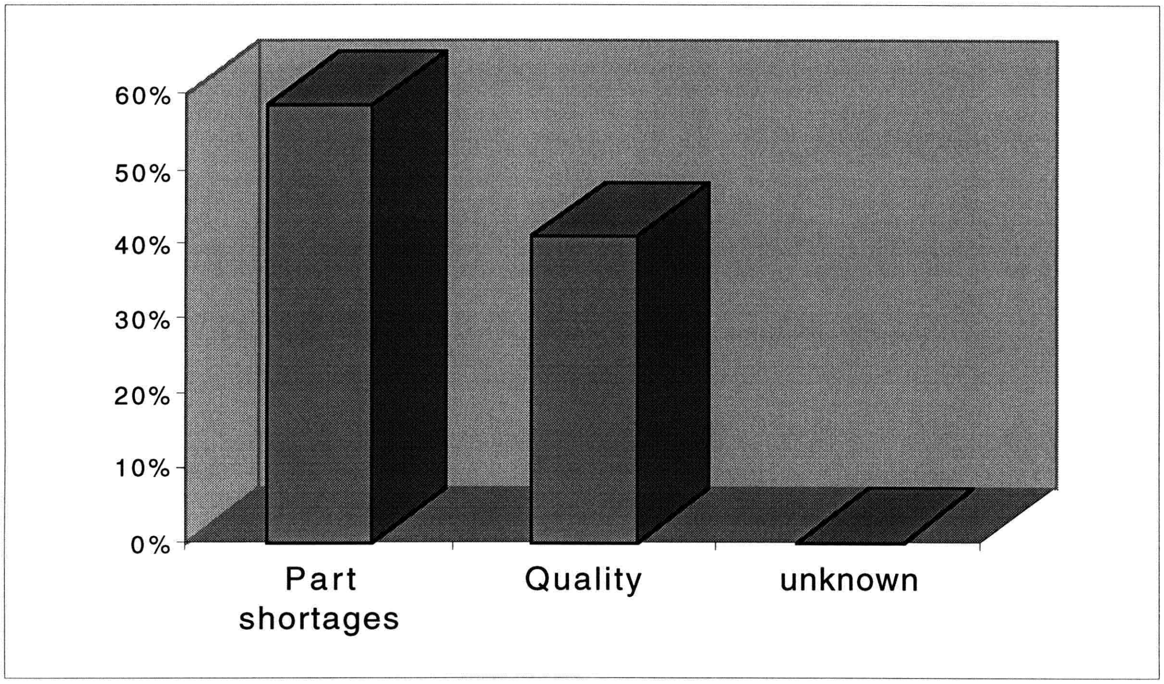


Figure 34 - reasons for delays in 4 A2 serial numbers

Before these layout changes had taken place, the delays due to part shortages were greater than those due to quality problems. We can see a difference in the proportions of the causes for delays in these new engines built with the new layout. Quality is now more of an equal source of delays compared to part shortages. Part shortages were still the main cause for delays in the commercial A2 engine. However, this might be due to the fact that the layout change in that line had not been completed yet.

As can be seen when comparing the throughput times of these new engine builds to the previous ones, the delays have not increased, but rather decreased. Throughput time is now shorter than it was previously. It can be deduced that the quality problems that cause delays have not increased, but that the part shortages have ceased to delay the engine builds as much as they used to.

This improvement in throughput time can be attributed only partly to the redesign of the layout. During this transitional period, overtime was increased noticeably. Overtime data was not available for this period, but from talking to foremen and assembly leaders, it was clear that overtime had been very high. It should also be noted that the layout changes were done gradually. Production was not interrupted during the re-distribution of equipment. Engine assembly lines were changed one at a time and each took approximately 5 months to be completely relocated.

Direct labor was not the only factor modified via overtime during this period. Expediting was also increased considerably. It cannot be determined conclusively what the impact of the factory floor redesign was. However, it would appear that it did contribute to make it easier to route parts through the factory more quickly. If this kind of effort were done concurrently with the restructuring of the supply chain and the production scheduling, it is very likely that the entire system would see permanent improvement. As mentioned before, the system cannot simply stop for a month and half while it waits for parts to catch up with assembly. However, the scenario described above would help the system get through the transition in a smoother way.

Variability Leading to Delays

At both sites A and B, a high level of variability was observed in the throughput time required to build engines, as can be seen in figure 11. Build times for the engines sampled at site C were not so varied. Figures 33 and 34 show the throughput times for engines C1 and C2 respectively. In both figures a horizontal line indicates the target throughput time at 23 and 21 days respectively.

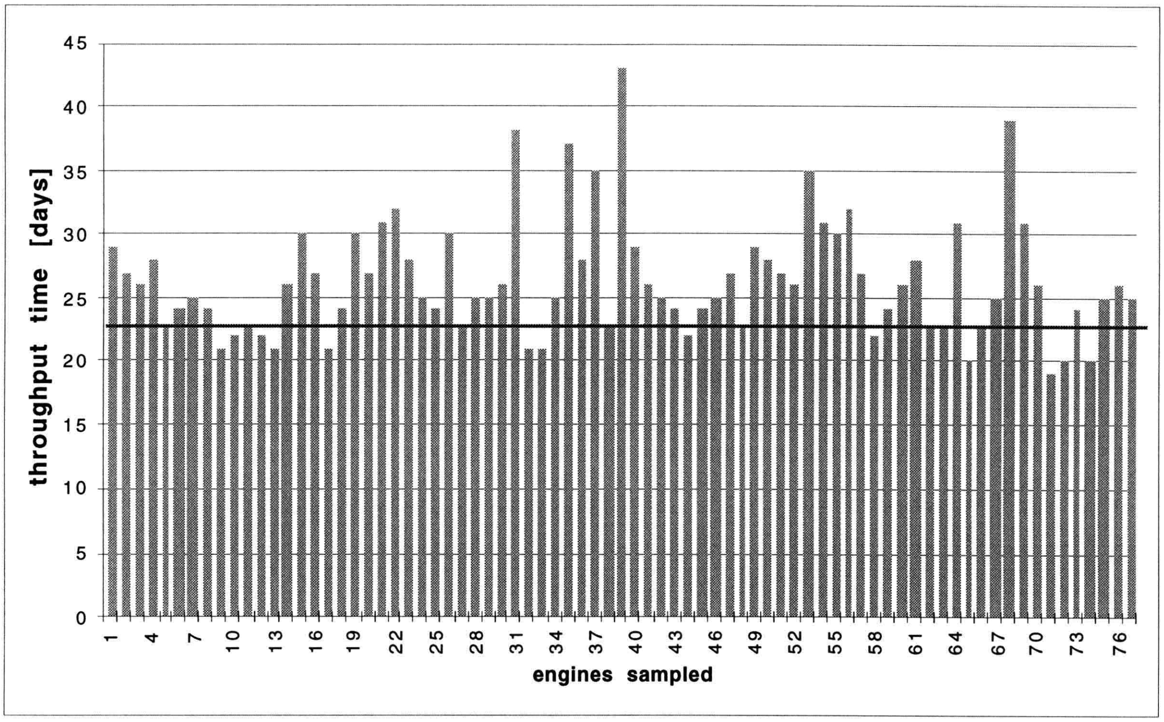


Figure 35 - build times for C1 sampled engines

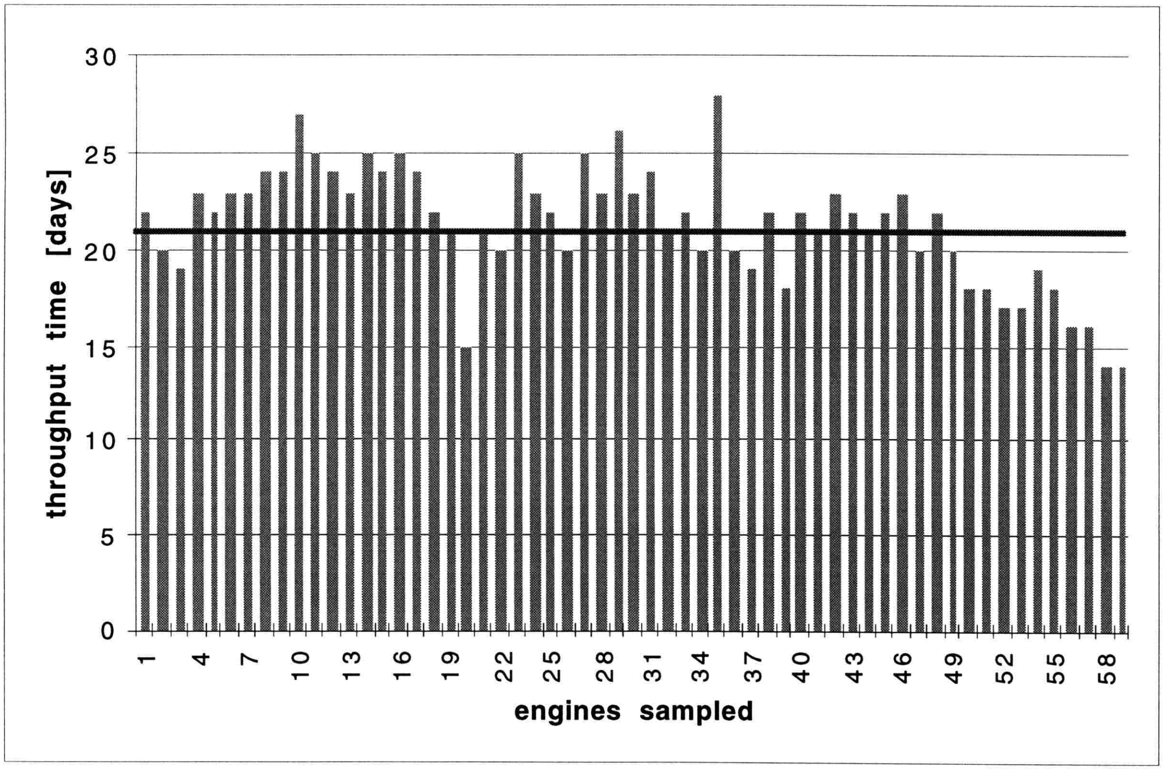


Figure 36 - build times for C2 sampled engines

High variability has one concrete effect on a production system. It tends to increase the planned throughput time. This happens because although the shortest build time cannot be shortened, the longest one can increase easily. In figure 35 we see a graphical representation of this effect. Point B represents the shortest build time possible. The first peak represents the build of units when variability is relatively small while the second one depicts the same builds when there is a higher variability. Generally in a production system, the planned throughput time is based on the actual mean throughput time. The mean of the distribution tends to shift to the right, that is, the mean throughput time, which usually follows the actual mean, tends to increase. A1 and A2 are the areas under the curves and are directly proportional to the total number of engines produced during the sampled period.

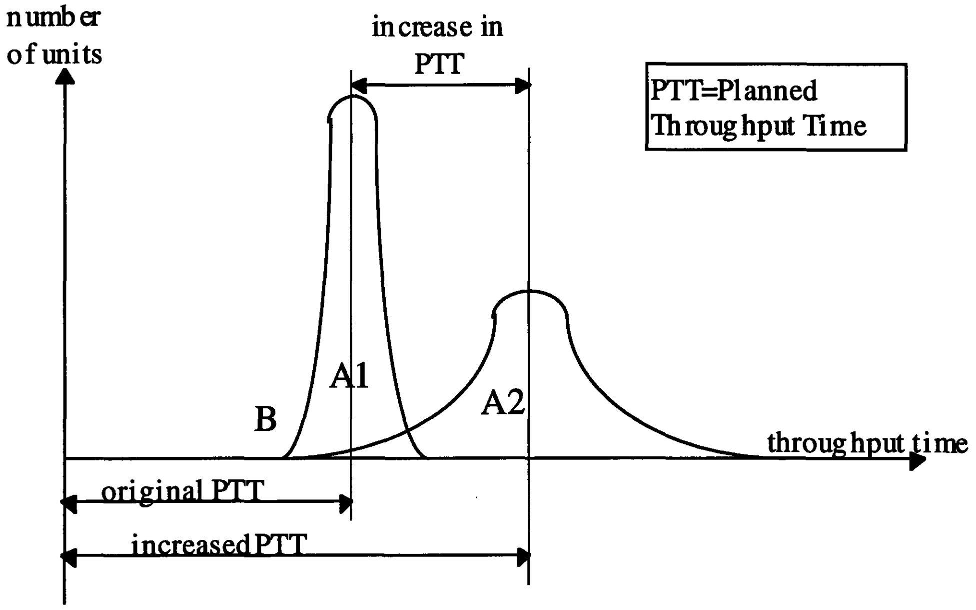


Figure 37 - increase in planned throughput time due to variability

5 LEM Comparison

The Lean Enterprise Model (LEM) is a systematic framework designed to organize the research results of the Lean Aircraft Initiative (LAI) and communicate these to its industry and government partners. It also serves as a model and catalyst for change in the defense aircraft industry.

The LEM encompasses lean enterprise principles and practices and is populated by research-based benchmarking data derived from surveys, case studies, and other research activities. The LEM serves as a reference to help LAI consortium members better understand the leanness of their own organizations and processes. It is intended to provide insights as to where they might direct lean efforts in the future.

As part of the research conducted at the three sites, the LEM and its enabling practices were compared to the policies and operations at the sites. Where ● is entered, the practice was implemented. ○ means there was a partial implementation where as ✕ was entered when the practice was not in use. A 'not observed' was entered when the observations could neither support the existence nor the non-existence of the practice.

Table 3 - Overarching Practice 1
Identify and Optimize Enterprise Flow

enabling practice	site A	site B	site C
Establish models and / or simulations to permit understanding and evaluation of the flow process	○	○	●
Reduce the number of flow paths	●	●	●
Minimize inventory through all tiers of the value chain	○	✕	●

enabling practice	site A	site B	site C
Reduce setup times	not observed	not observed	●
Implement process owner inspection throughout the value chain	×	×	●
Strive for single piece flow	●	○	●
Minimize space utilized and distance traveled by personnel and material	×	×	●
Synchronize production and delivery throughout the value chain	○	×	●
Maintain equipment to minimize unplanned stoppages	×	not observed	○

Table 4 - Overarching Practice 2
Assure Seamless Information Flow

enabling practice	site A	site B	site C
Make processes and flows visible to all stake-holders	×	×	●
Establish open and timely communications among all stakeholders	×	×	●
Link databases for key functions throughout the value chain	×	×	●
Minimize documentation while ensuring necessary data traceability and availability	×	×	●

Table 5 - Overarching Practice 3
Optimize Capability and Utilization of People

enabling practice	site A	site B	site C
Establish career and skill development programs for each employee	×	×	○
Ensure maintenance and upgrading of critical skills	×	×	○
Analyze workforce capabilities and needs to provide for balance of breadth and depth of skills/knowledge	○	not observed	○
Broaden jobs to facilitate the development of a flexible workforce	×	×	×

Table 6 - Overarching Practice 4
Make Decisions at Lowest Possible Level

enabling practice	site A	site B	site C
Establish multidisciplinary teams organized around processes and products	not observed	not observed	●
Delegate or share responsibility for decisions throughout the value chain	not observed	not observed	●
Empower people to make decisions at the point of work	×	○	●
Minimize hand-offs and approvals within and between line and support activities	not observed	not observed	×
Provide environment and well-defined processes for expedited decision-making	not observed	not observed	×

Table 7 - Overarching Practice 8
Promote Lean Leadership at all Levels

enabling practice	site A	site B	site C
Flow-down lean principles, practices and metrics to all organizational levels	not observed	not observed	●
Instill individual ownership throughout the workforce in all products and services provided	not observed	not observed	○
Assure consistency of enterprise strategy with lean principles and practices	×	×	●
Involve union leadership in promoting and implementing lean practices	not observed	not observed	●

Table 8 - Overarching Practice 10
Nurture a Learning Environment

enabling practice	site A	site B	site C
Capture, communicate and apply experience-generated learning	not observed	not observed	●
Perform benchmarking	not observed	×	●
Provide for interchange of knowledge from and within the supplier network	not observed	not observed	not observed

Overarching practices number 5, 6, 7, 9 ,11 and 12, which cover product and process development, relationships, customer relations, process improvement and capability and stability and environmental changes, were not covered during the study.

It can be observed that at site C a majority of the practices contained in the LEM were implemented. This was not the case at sites A and B.

When the most important performance measures of the production systems are compared to their respective 'LEM score', correlations are clear. The 'LEM score' is calculated by grading the full implementation of a particular enabling practice as 2 points, the partial implementation as 1 point and no points for the lack of implementation. The sum of these specific grades becomes the 'LEM score'. It should be noted that this score is relatively subjective due to the fact that every practice was given equal weight, and the accurate evaluation of each practice should, strictly speaking, be done after careful evaluation of the production system as it refers to that particular practice; something that was not possible to do during this study due to time and man-power restrictions. Figure 38 shows the percentage of on-time deliveries as a function of the 'LEM score' of the sites.

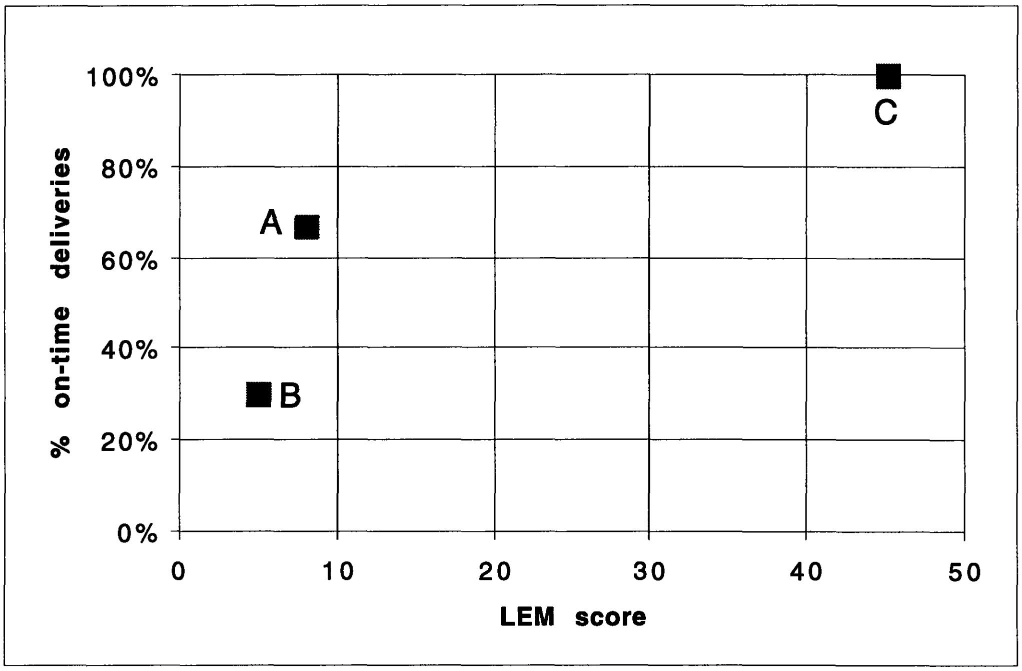


Figure 38 - LEM score vs. % on-time deliveries

Indeed, a higher 'LEM score' appears to be related to a higher percentage of on-time deliveries. Figure 39 shows average delay to finish an engine vs. the 'LEM score'. Figure 40 presents the variation in throughput time, another important symptom of a production system, as a function of the 'LEM score'.

It can be seen that the performance measures considered, throughout the study, as crucial to a production system are in fact related to the level of implementation of recognized lean practices, such as those included in the LEM.

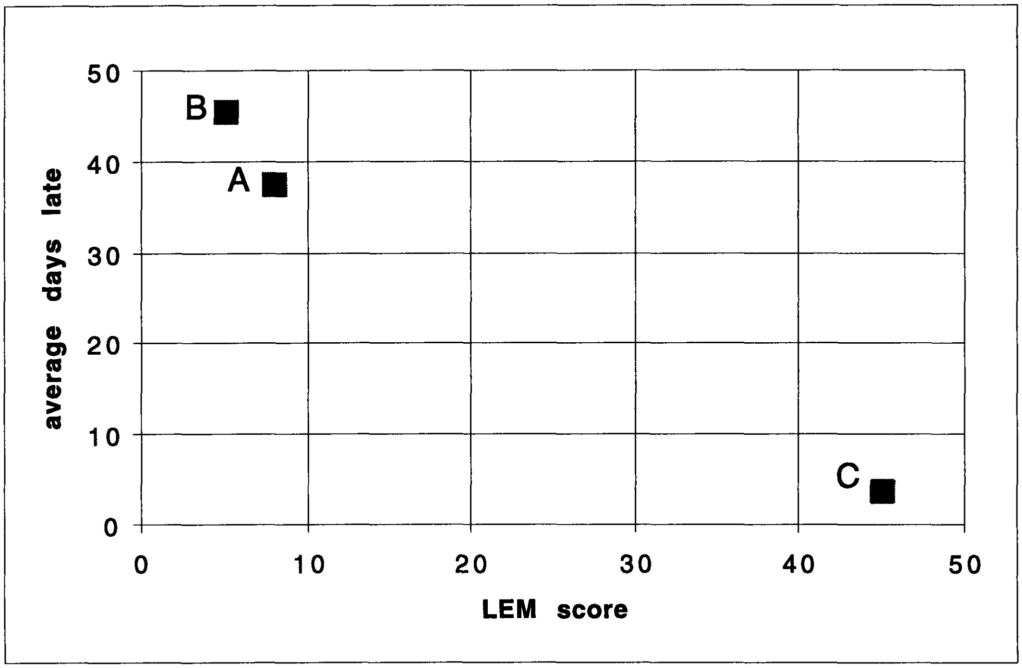


Figure 39 - LEM score vs. conformance to schedule

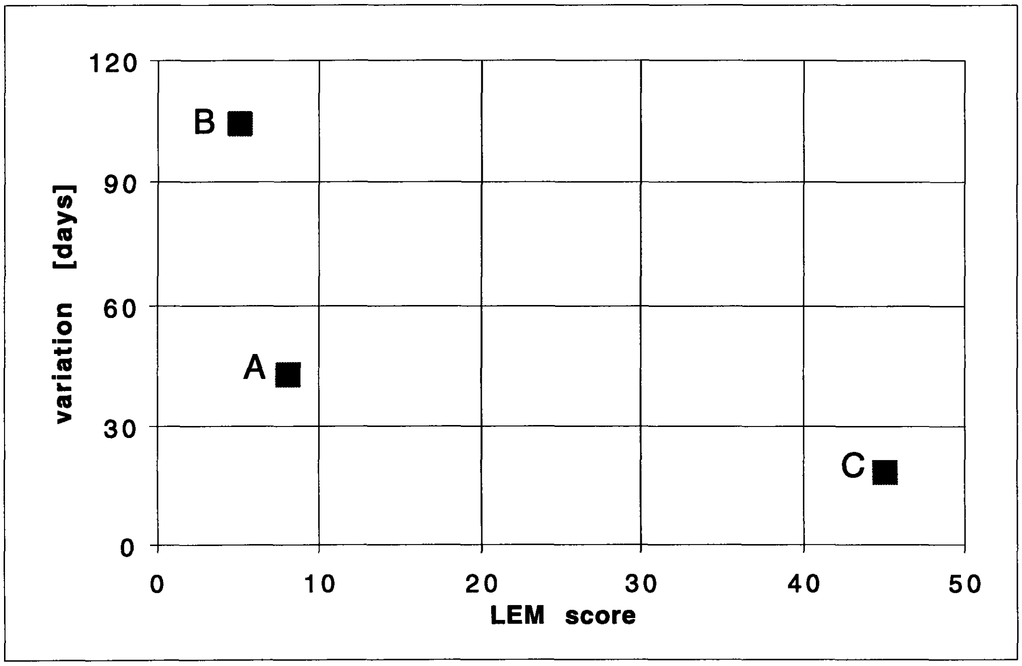


Figure 40 - throughput time variation vs. LEM score

6 Conclusions

Usually when production systems are compared, and one of them performs, in terms of throughput time and conformance to schedule, better than the others, the best that can be hoped for is a relative comparison. The systems are not similar and the comparison is not really on common ground, but more on an extrapolated level. The uniqueness of this study is that the products the systems studied manufacture can be compared as 'apples to apples'. While it is true that the engines produced do not have identical complexity levels and part counts, they are all manufactured in the same way. The relationship between total part count and planned build time supports this. It was also confirmed by observing the various building procedures at the factories that they are essentially built the same way. In fact, the system performance is independent of complexity.

Once this common ground has been established and verified, we can proceed to analyze the most meaningful variables that these systems have; inputs and outputs. The inputs, those aspects which can be directly controlled by the people who run the system, are:

- scheduling systems,
- factory layouts,
- part flow paths,
- supply chain management,
- human resources management,
- and ways of dealing with perturbations.

We saw that two of the systems studied, deal with these issues in mostly the same way (sites A and B) and perform similarly in terms of the time it takes them to build a unit compared to the time they had originally planned. There is also a similarity in their conformance to their schedule in terms of the difference between the planned and the actual finish date of each build.

On the other hand, site C handles its scheduling in a different way, requires its supplier to deliver in a different way and has its floor designed in a different way. Its scheduling system is one which takes into account perturbations on the assembly floor. Its suppliers deliver only complete kits of parts and are informed periodically of the status of the build requirements. Its factory is laid out in a product-oriented way rather than a job shop environment. It does not start a build until all required parts are available at the plant. Still, we saw no strong improvement in this kind of production system when only layout redesign was done. It is more important to first address the problems in the supply chain.

Sites A and B, as everyone else who has problems, need to tackle their biggest problem first. That problem is shortage of parts. Quality issues, station availability and worker flexibility are somewhat secondary issues currently because of the overwhelming number of part shortages. Site C, however, can start to engineer ways to solve secondary problems such as part quality and worker and station flexibility because it no longer faces the burden of having to chase parts. MRP is a good planning tool, but not such a good schedulingaid.

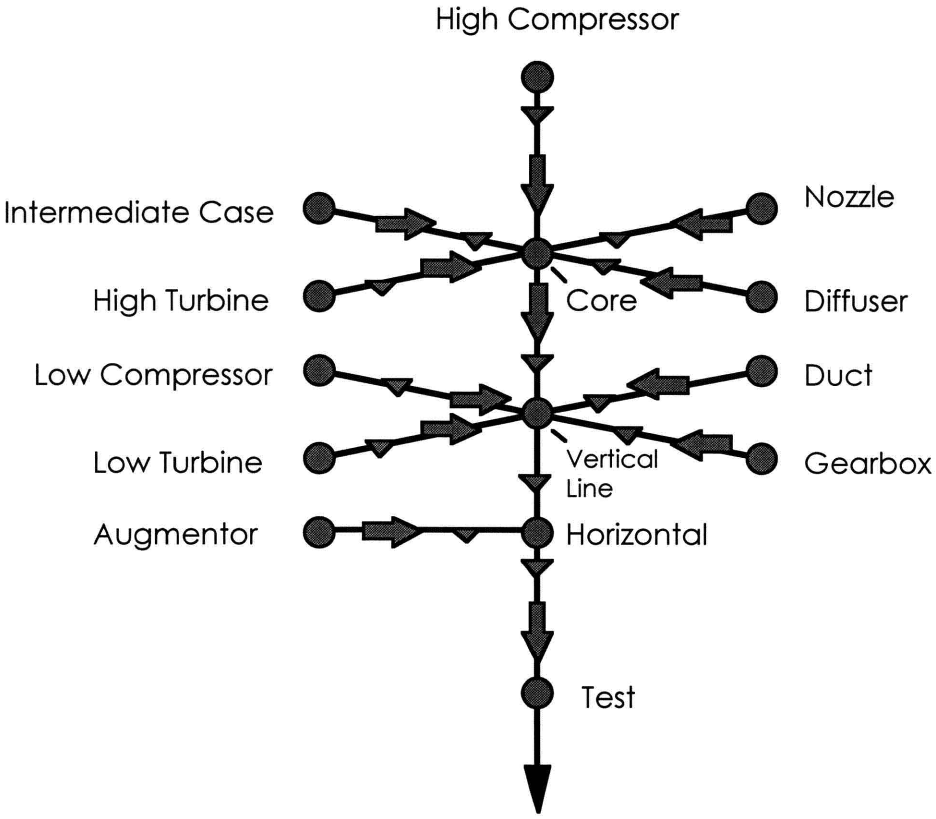
Also, we concluded that despite differences in product characteristics, military and commercial engines face similar problems during production and the individual production systems perform similarly in their production of either type of engine.

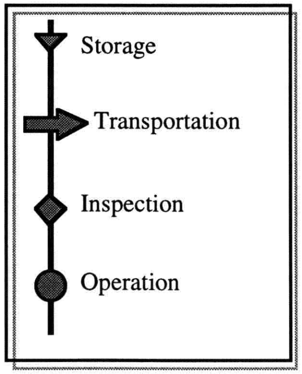
Our hypothesis that lean production principles can be applied in the aircraft industry has been proven. While it is true that site C could still improve many aspects of its production system, such as part quality, and operator and station flexibility, it has achieved (at least in 80% of its parts-worth) one very important aspect of production which is considered to be lean; a pull system. It has managed to produce engines always on time and without the need to have people whose only job is to chase parts in the system. It also has reduced its variability greatly compared to the rest of the industry.

In an increasingly demanding market, the ability to deliver products on time and to customer requirements without having to spend excessive resources is essential. Other aircraft sectors, such as airframes and electronics, could learn from examples such as this one. In the end, their production systems would be more efficient and responsive; leaner.

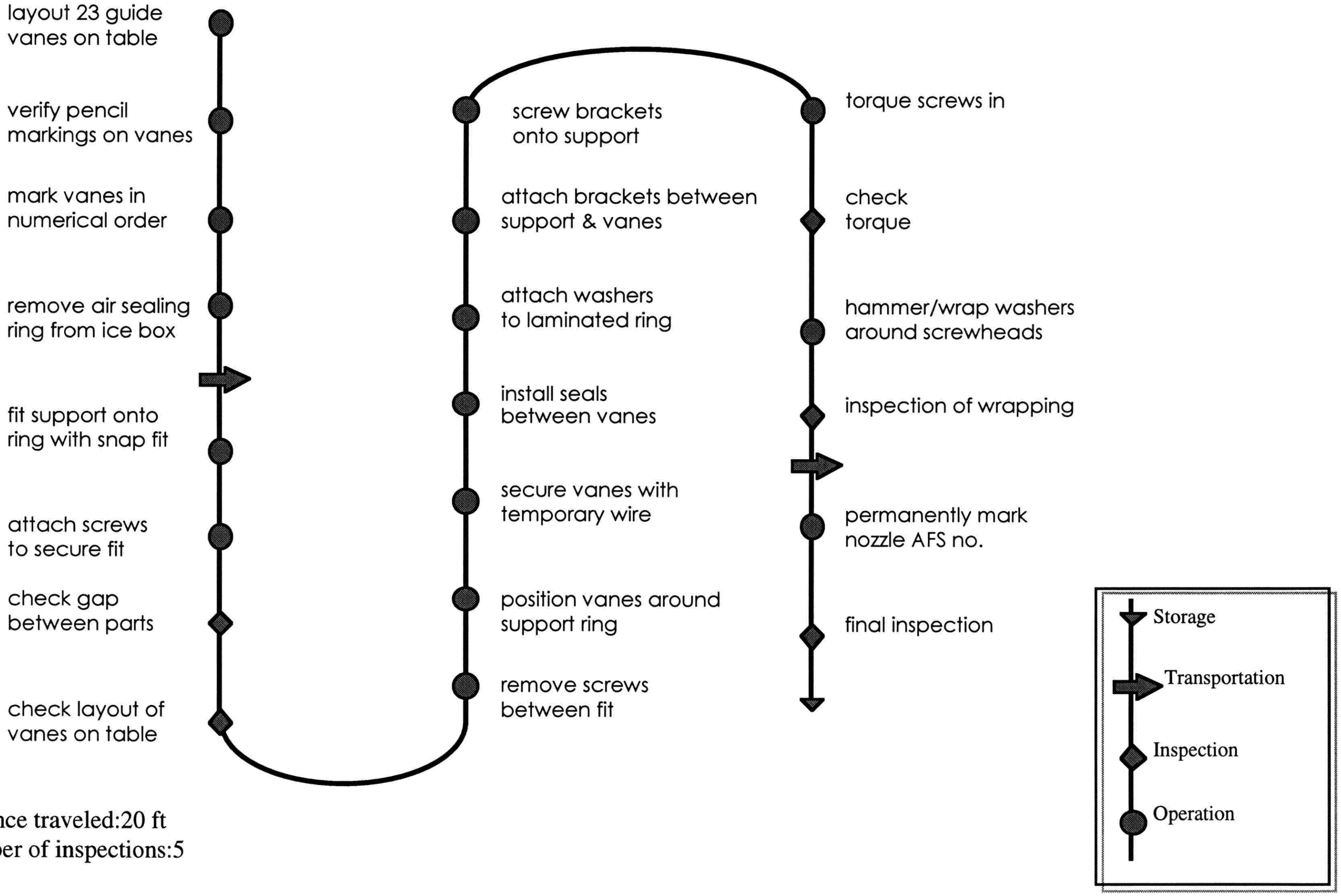
Appendix A - Process Maps

A1 • Engine Module Flow



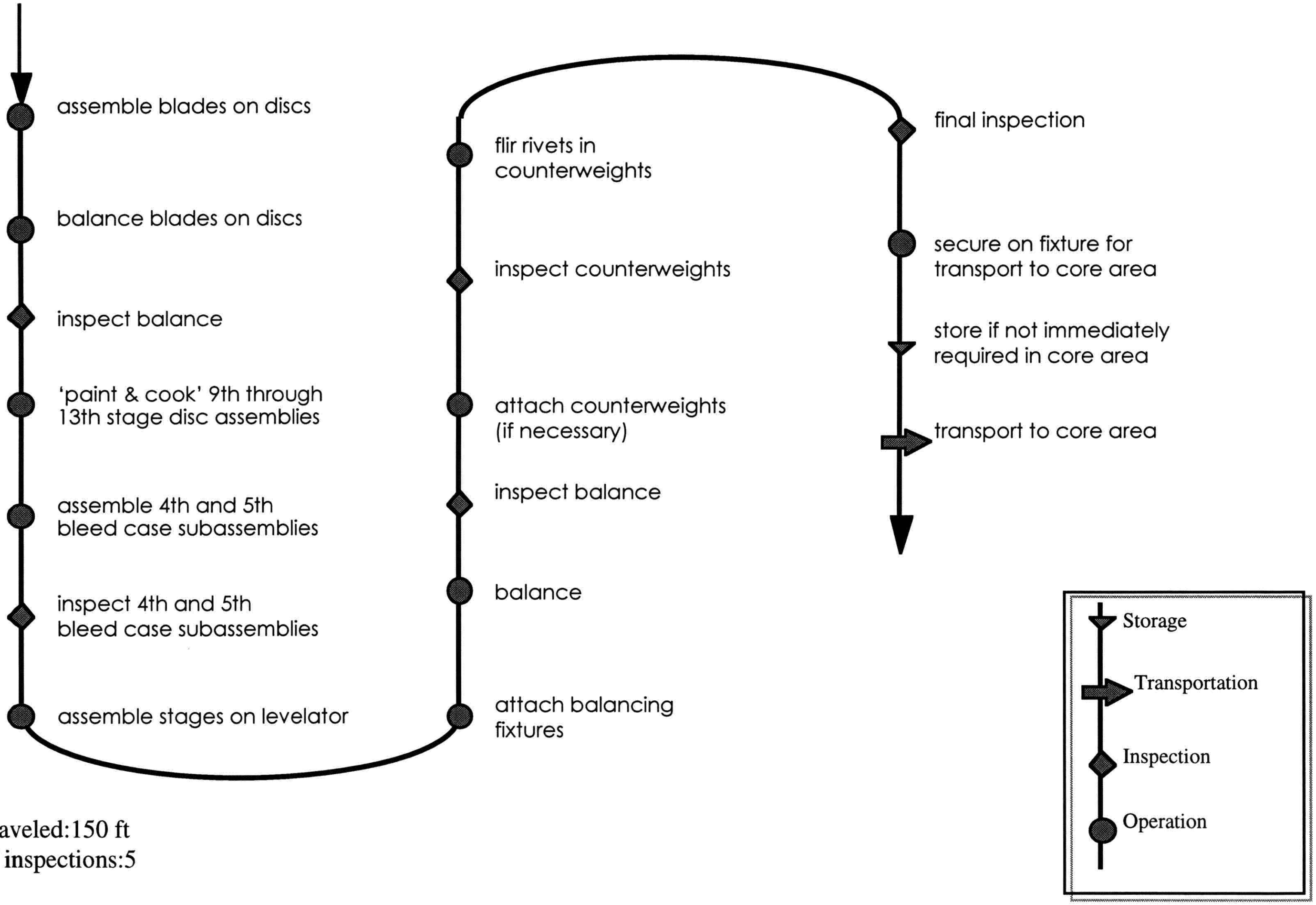


A1 • Nozzle Module



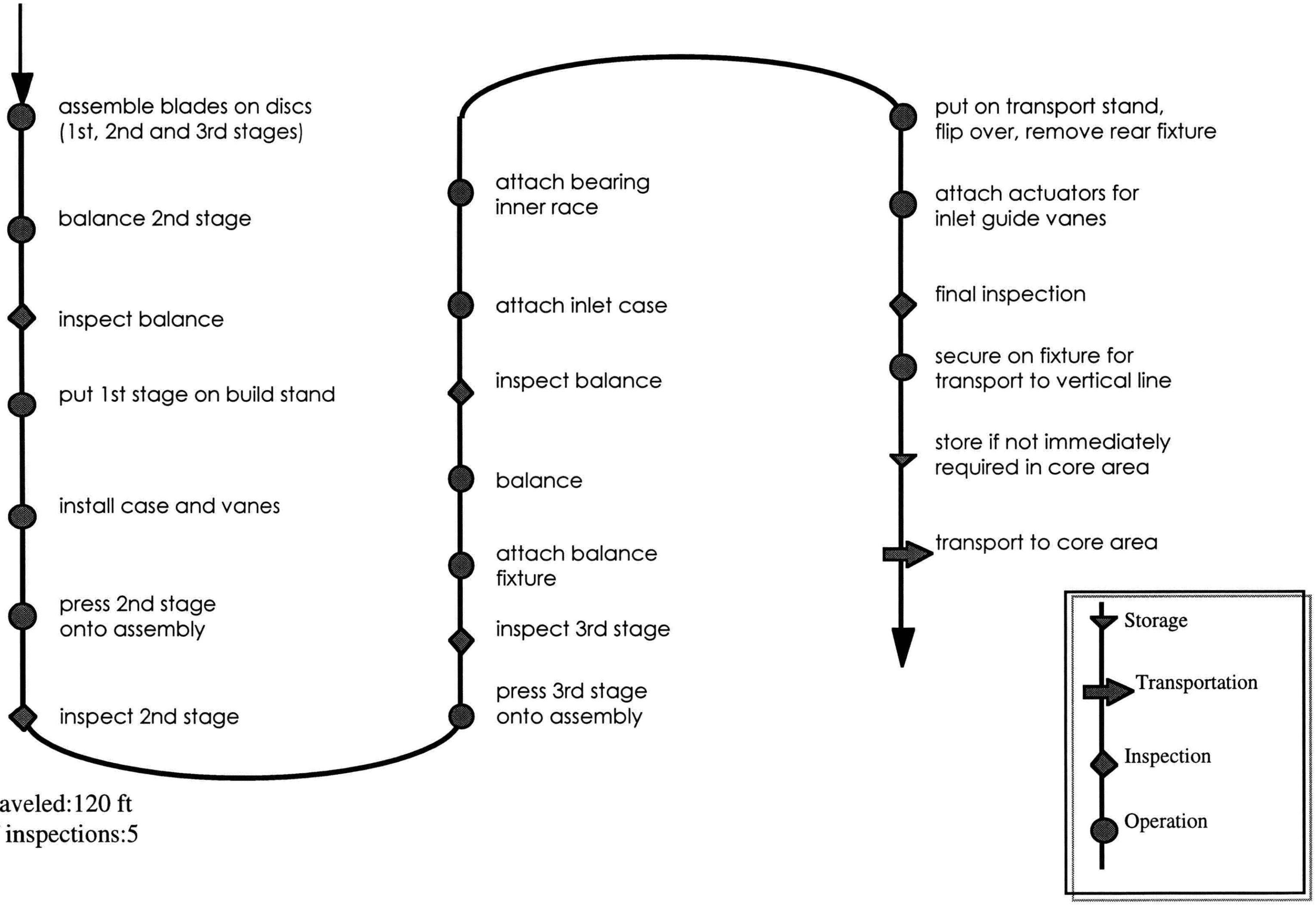
distance traveled:20 ft
number of inspections:5

A1 • High Compressor Module



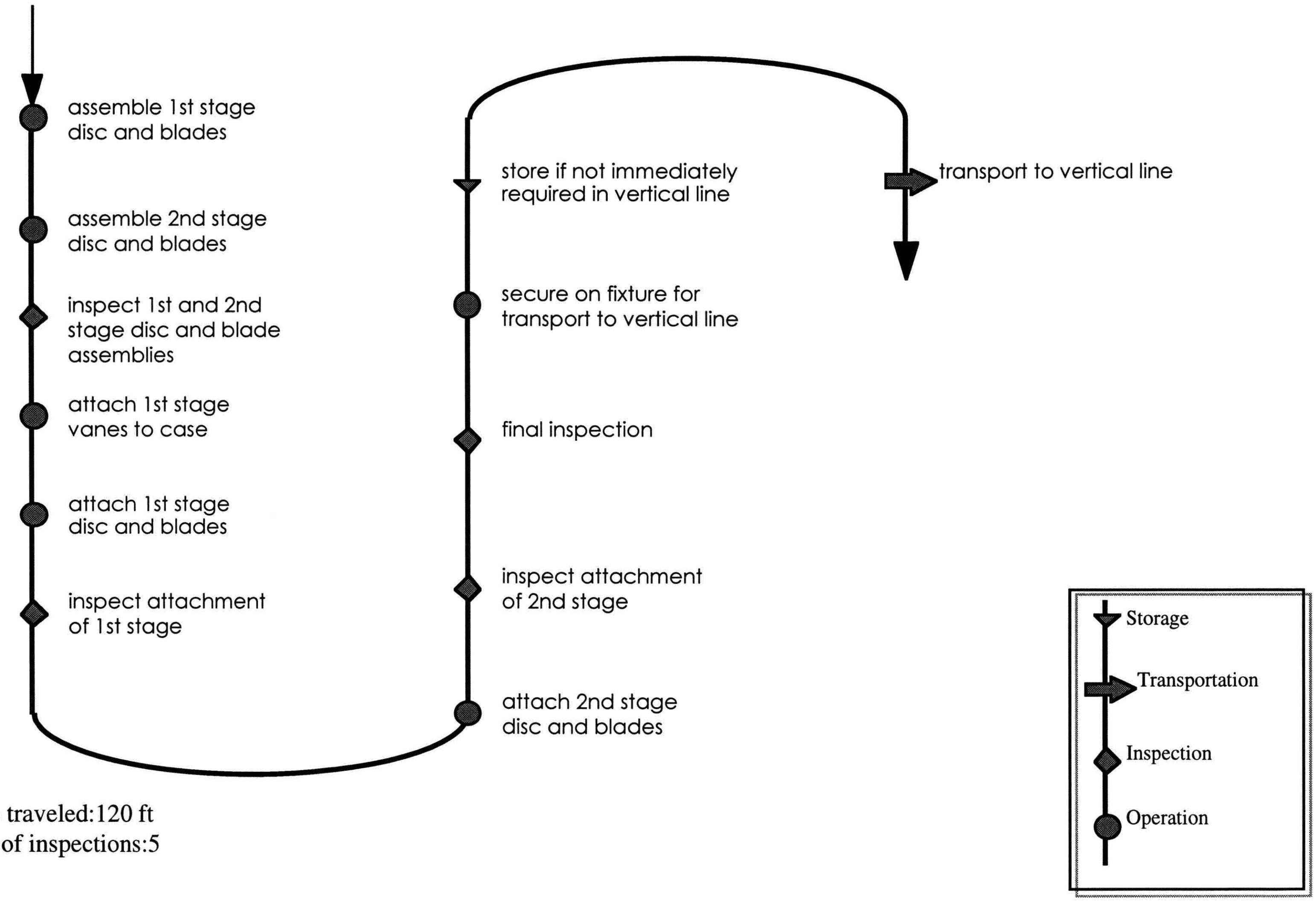
distance traveled:150 ft
number of inspections:5

A1 • Low Compressor Module



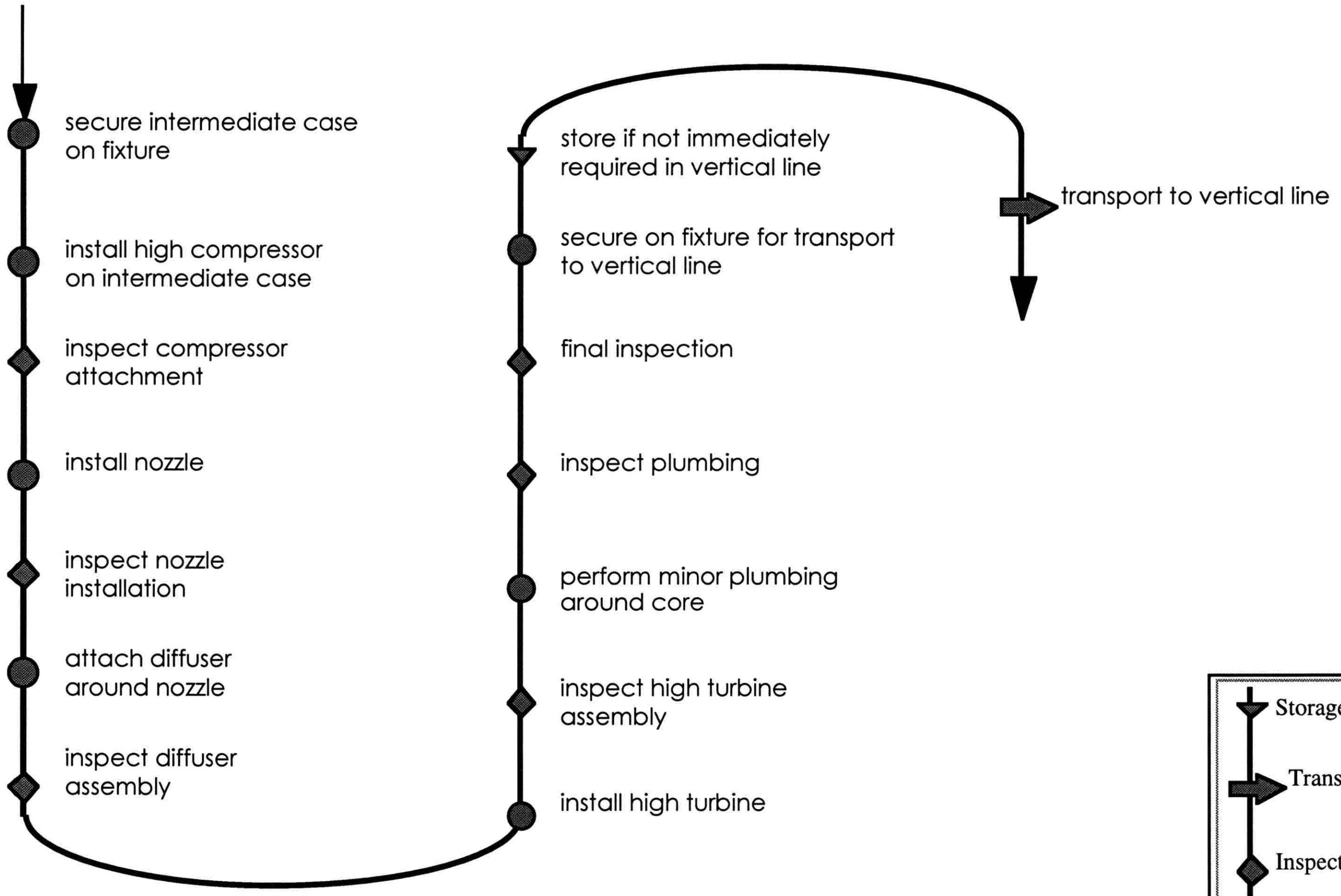
distance traveled:120 ft
number of inspections:5

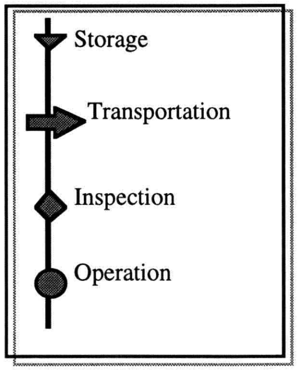
A1 • Low Turbine Module



distance traveled:120 ft
number of inspections:5

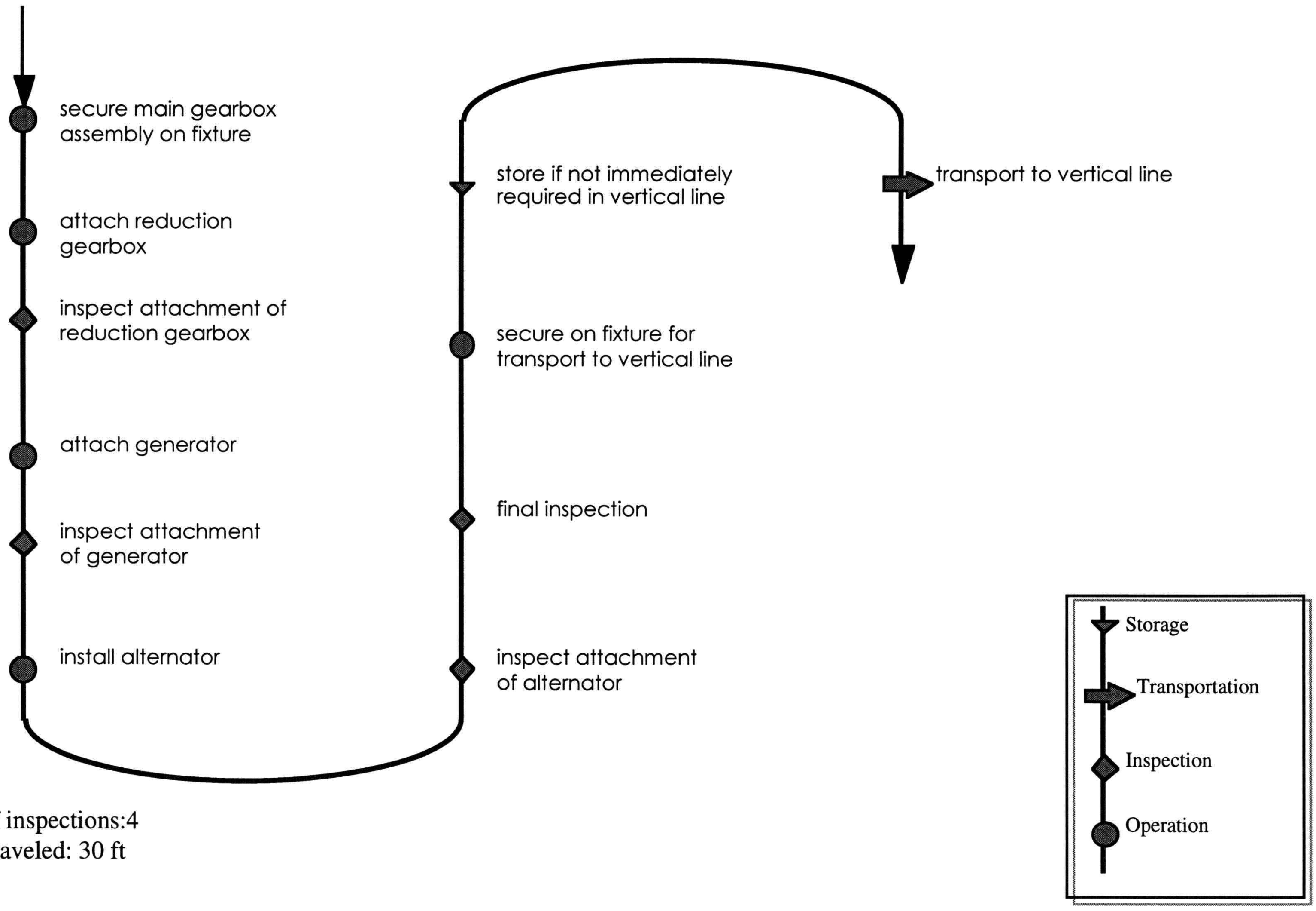
A1 • Core Module





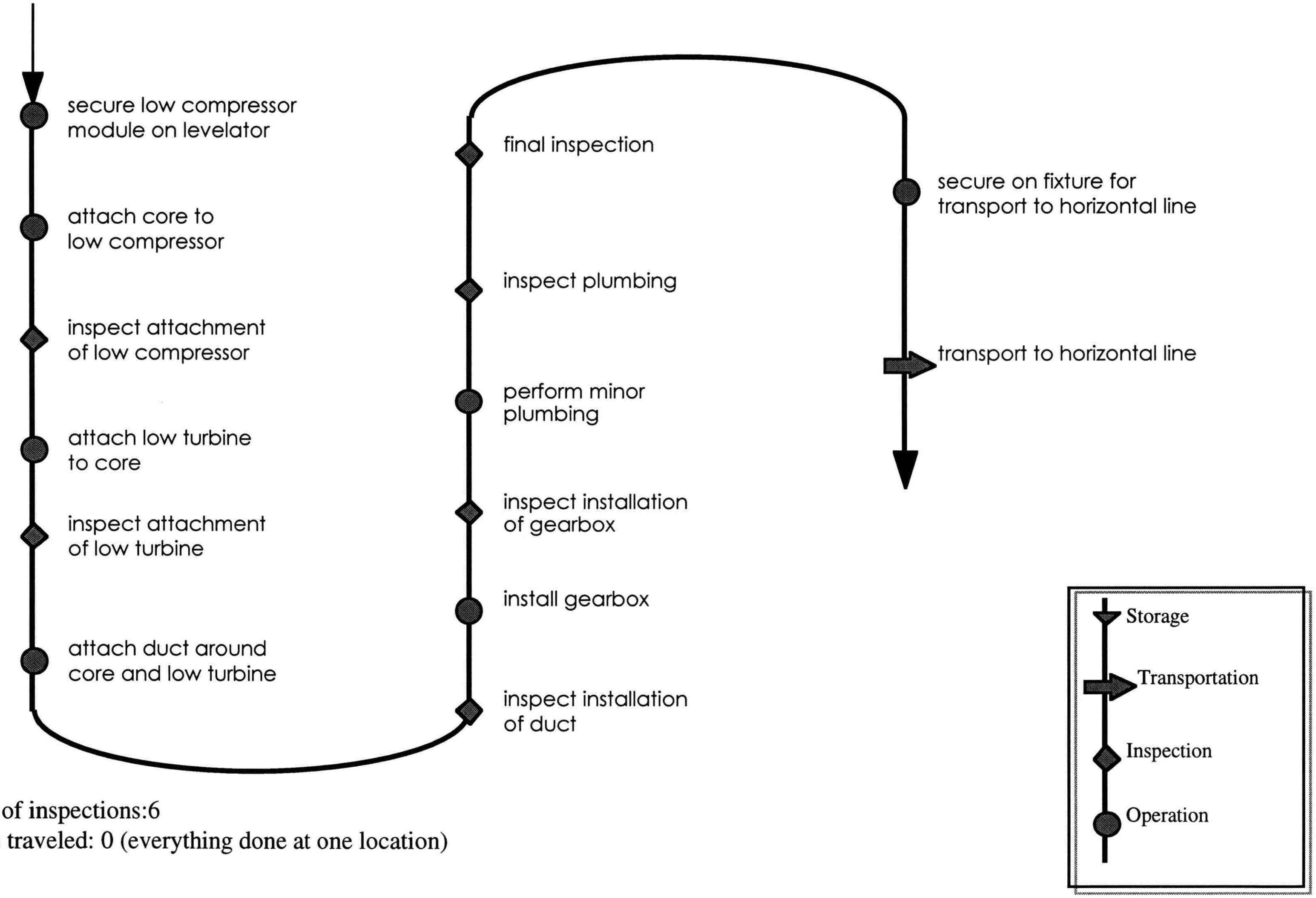
number of inspections:6
distance traveled: 0 (everything done at one location)

A1 • Gearbox Module



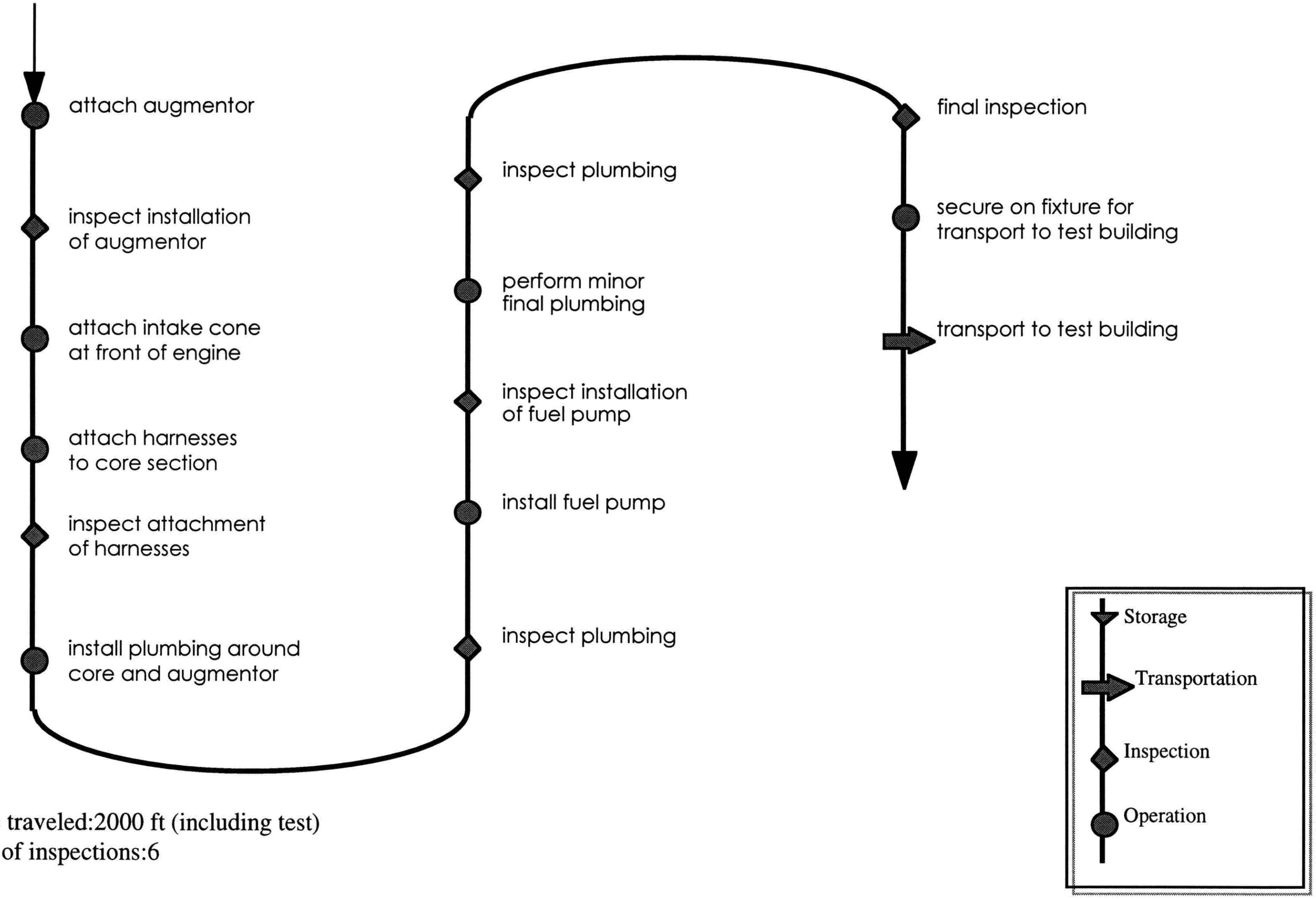
number of inspections:4
distance traveled: 30 ft

A1 • Vertical Assembly Line



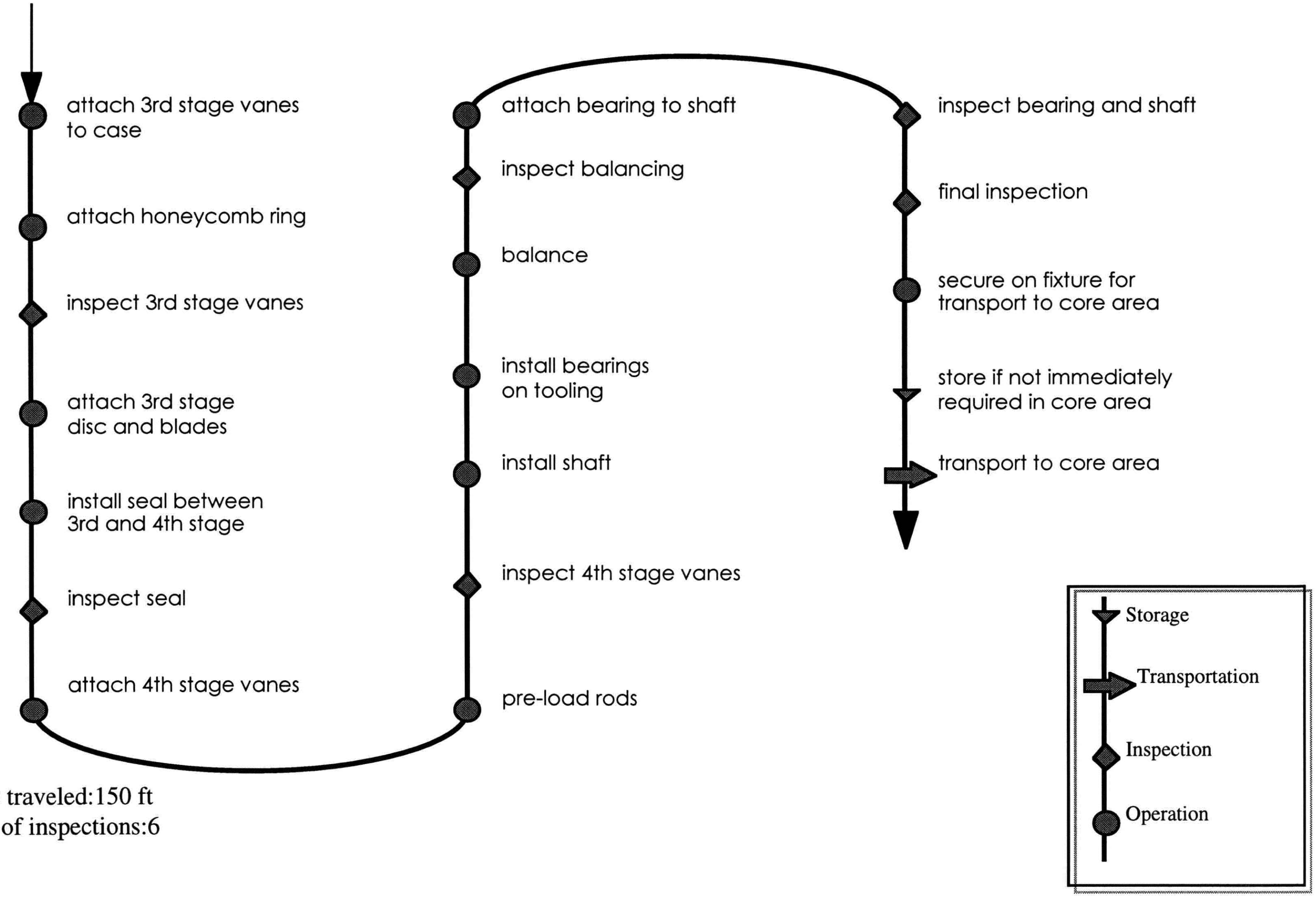
number of inspections:6
distance traveled: 0 (everything done at one location)

A1 • Horizontal Assembly Line



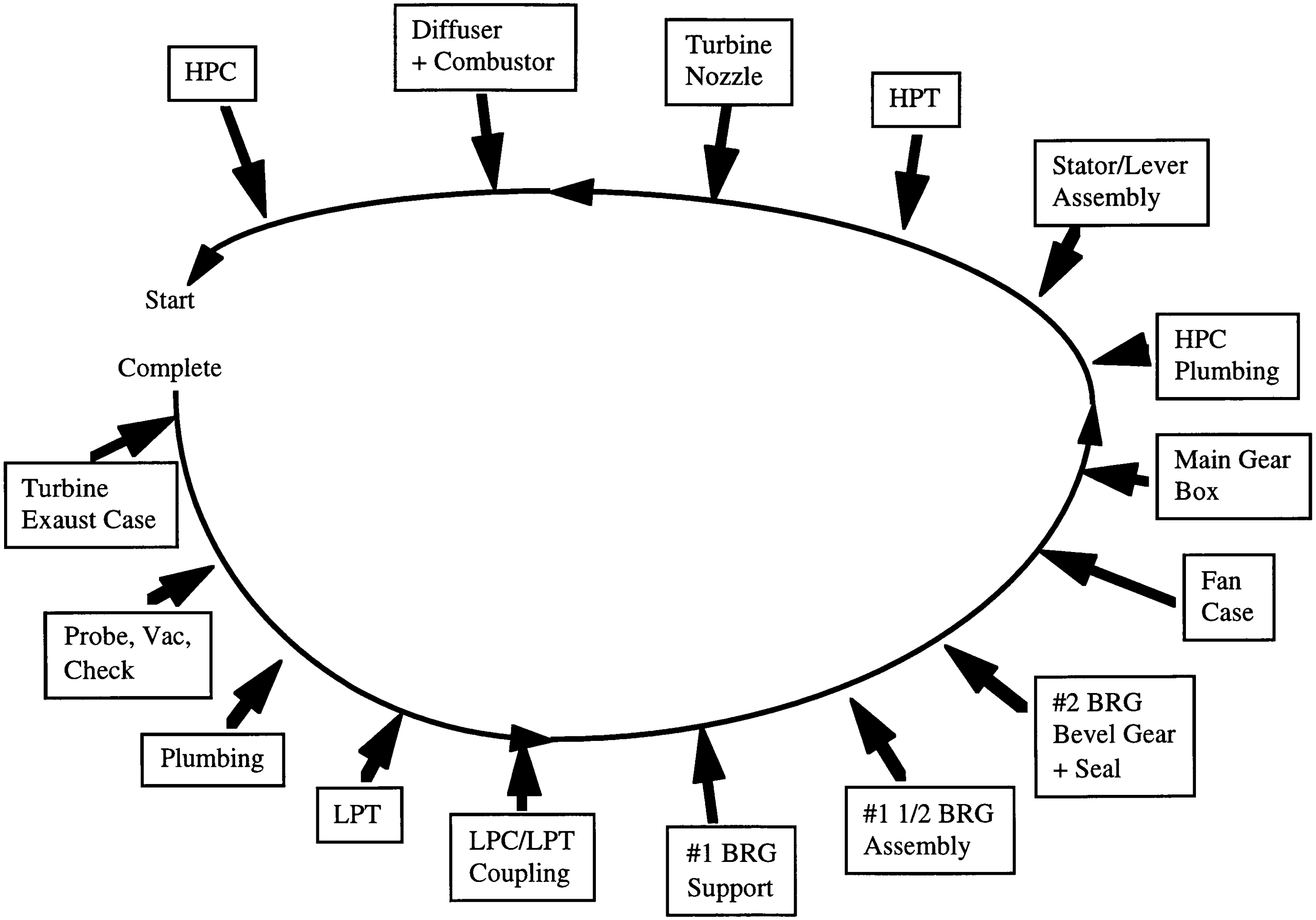
distance traveled:2000 ft (including test)
number of inspections:6

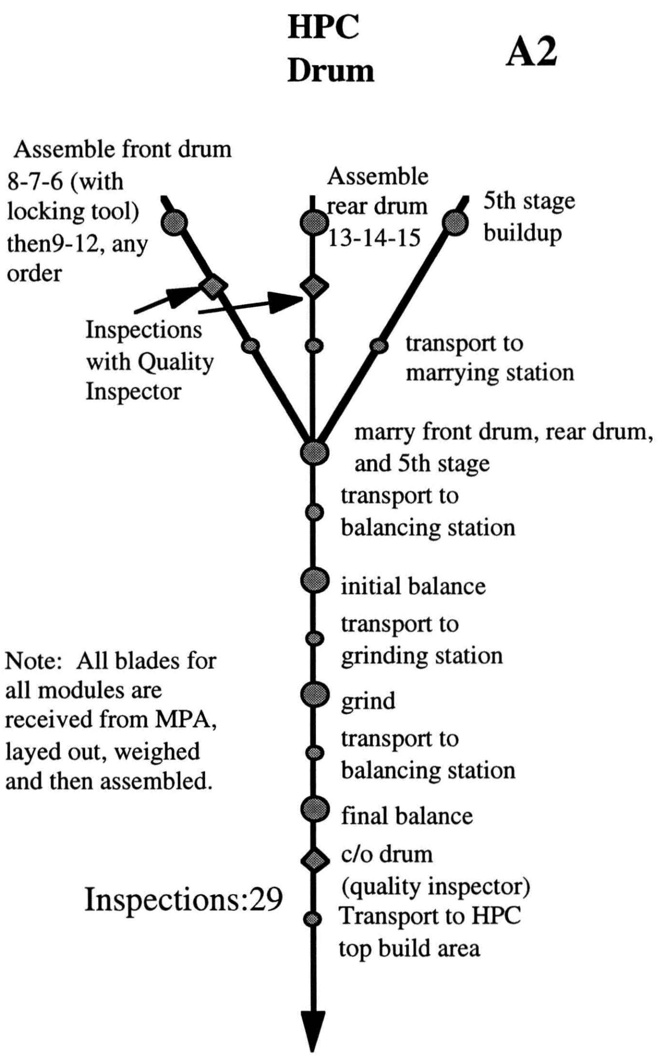
A1 • High Turbine Module



distance traveled:150 ft
number of inspections:6

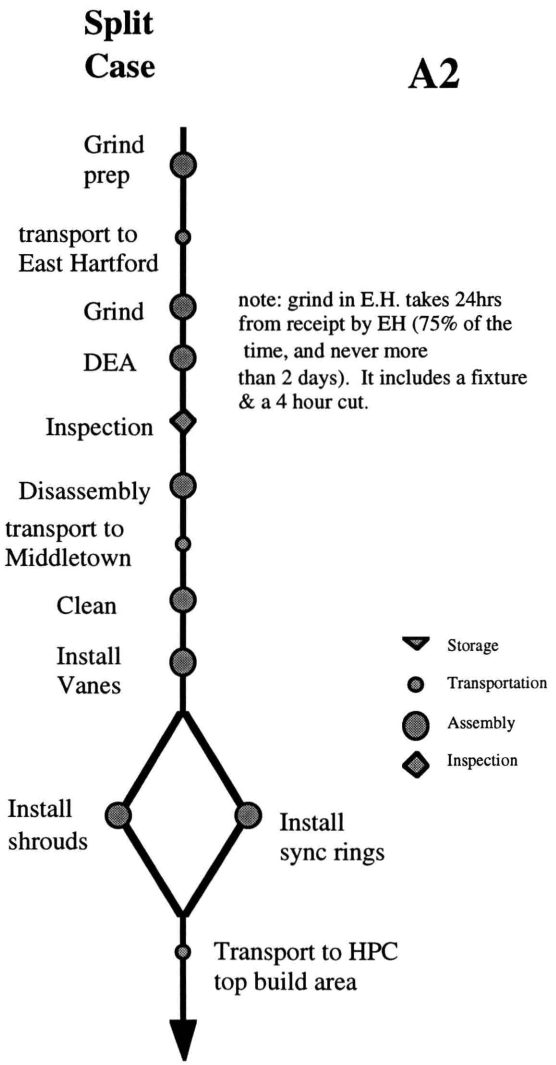
A2 • Engine Module Flow





Note: All blades for all modules are received from MPA, layed out, weighed and then assembled.

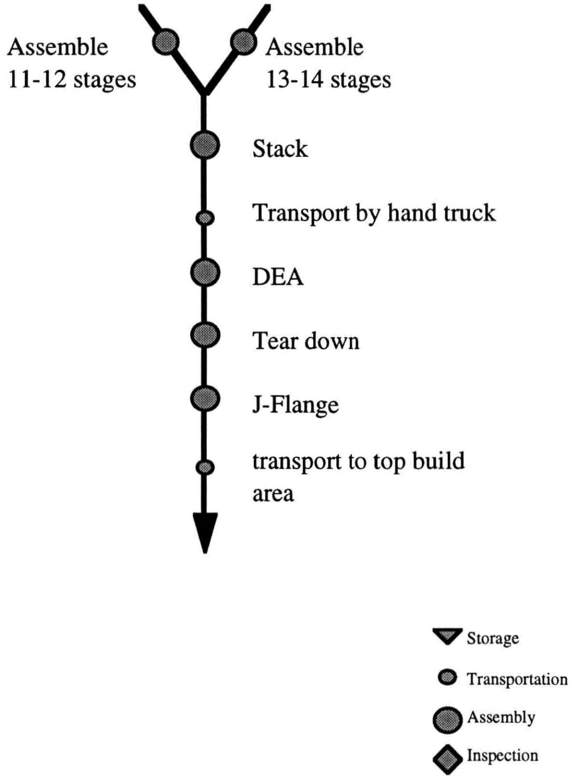
Inspections:29



note: grind in E.H. takes 24hrs from receipt by EH (75% of the time, and never more than 2 days). It includes a fixture & a 4 hour cut.

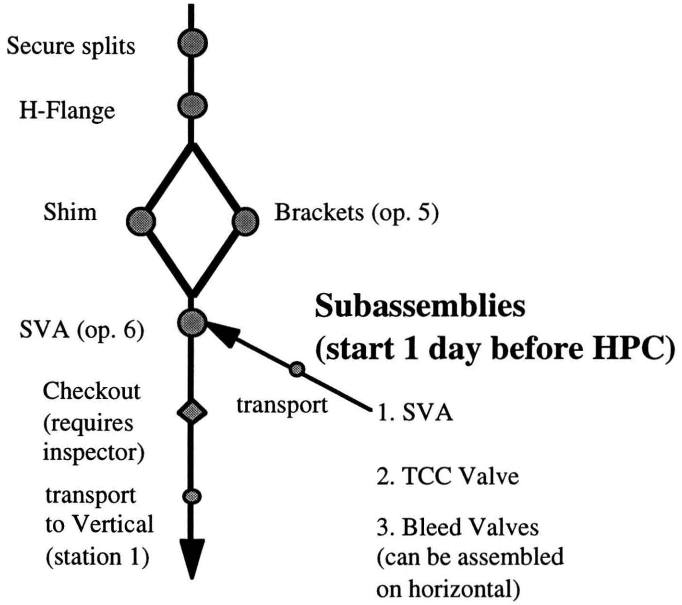
A2

Stators



A2

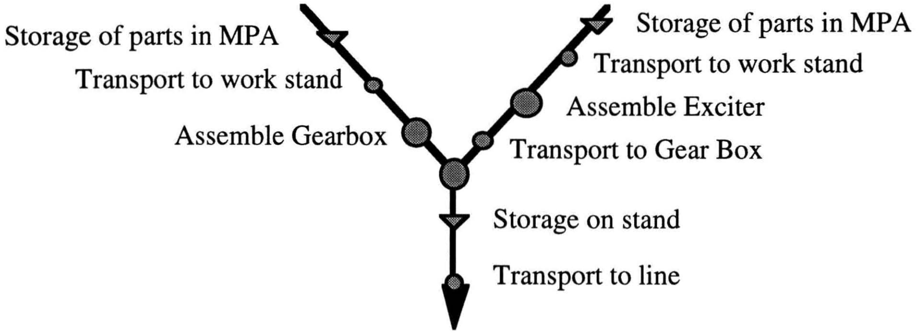
High Compressor/ Top Build



Inspections: 37 (HPC except drum)

Distance traveled: 632 ft

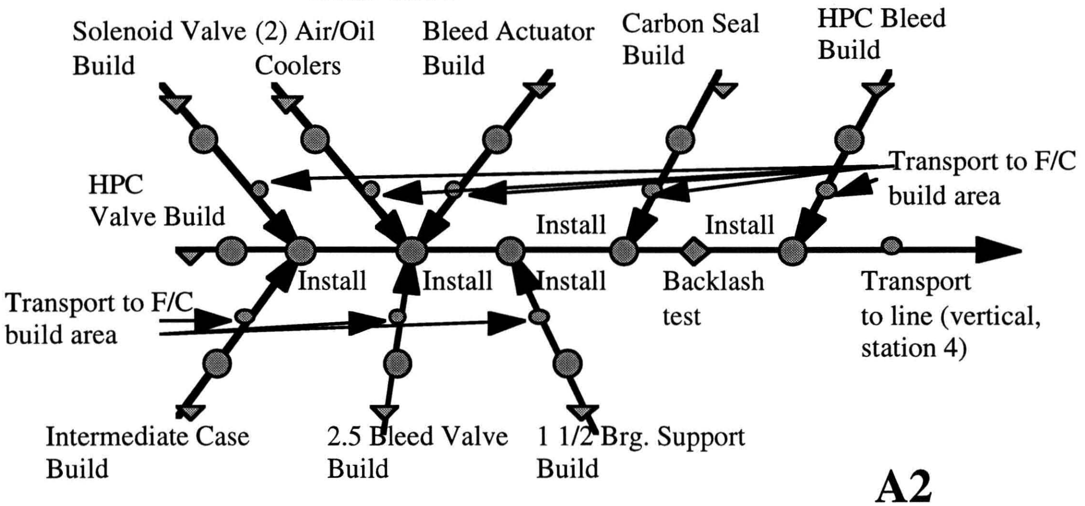
Gearbox-Exciter



Distance
Traveled: 640’
Inspections:3

A2

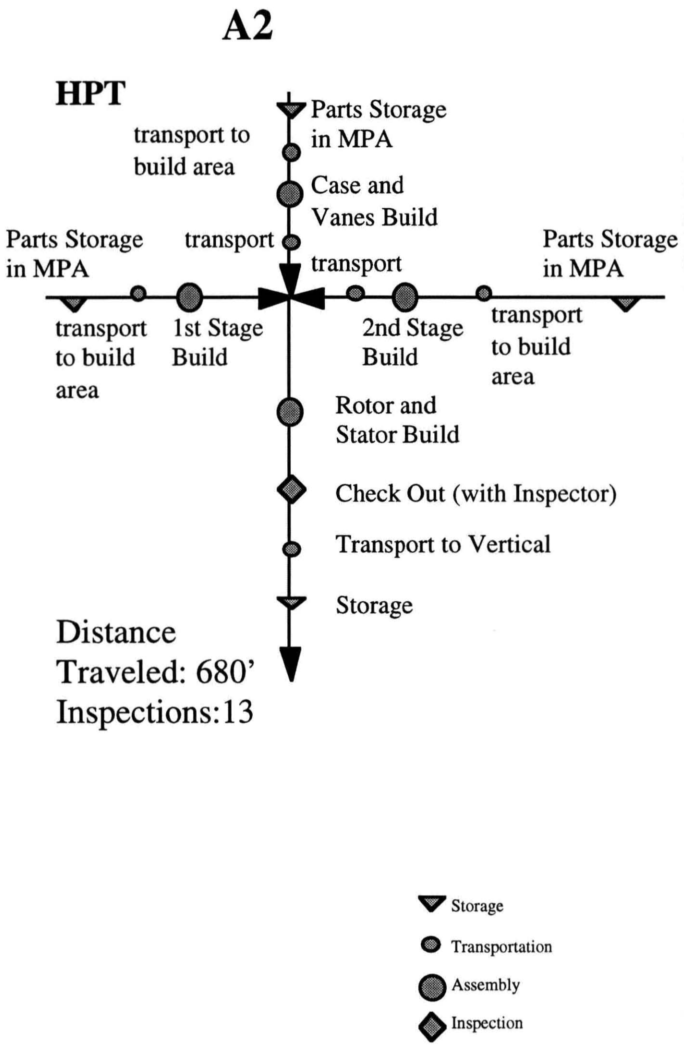
Fan Case



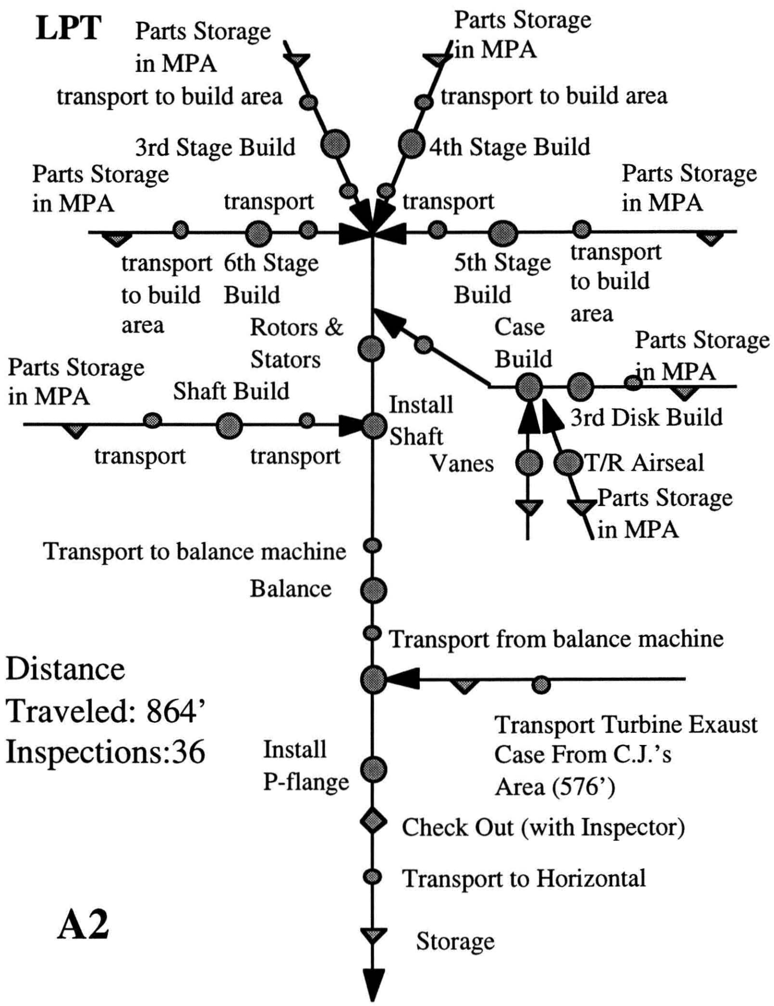
Distance
Traveled: 420’
Inspections:25

A2

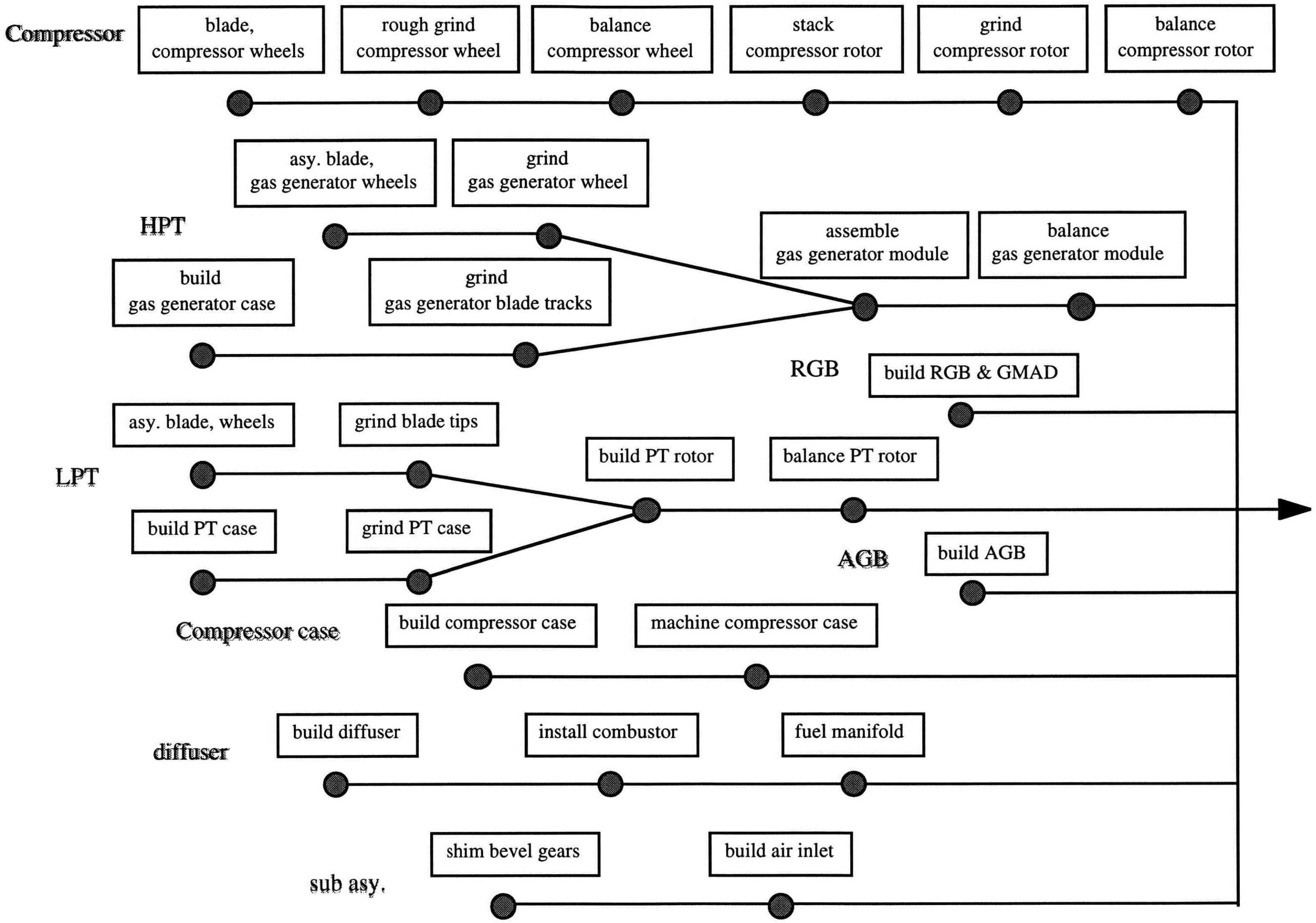
▼ Storage
● Transportation
● Assembly
◆ Inspection



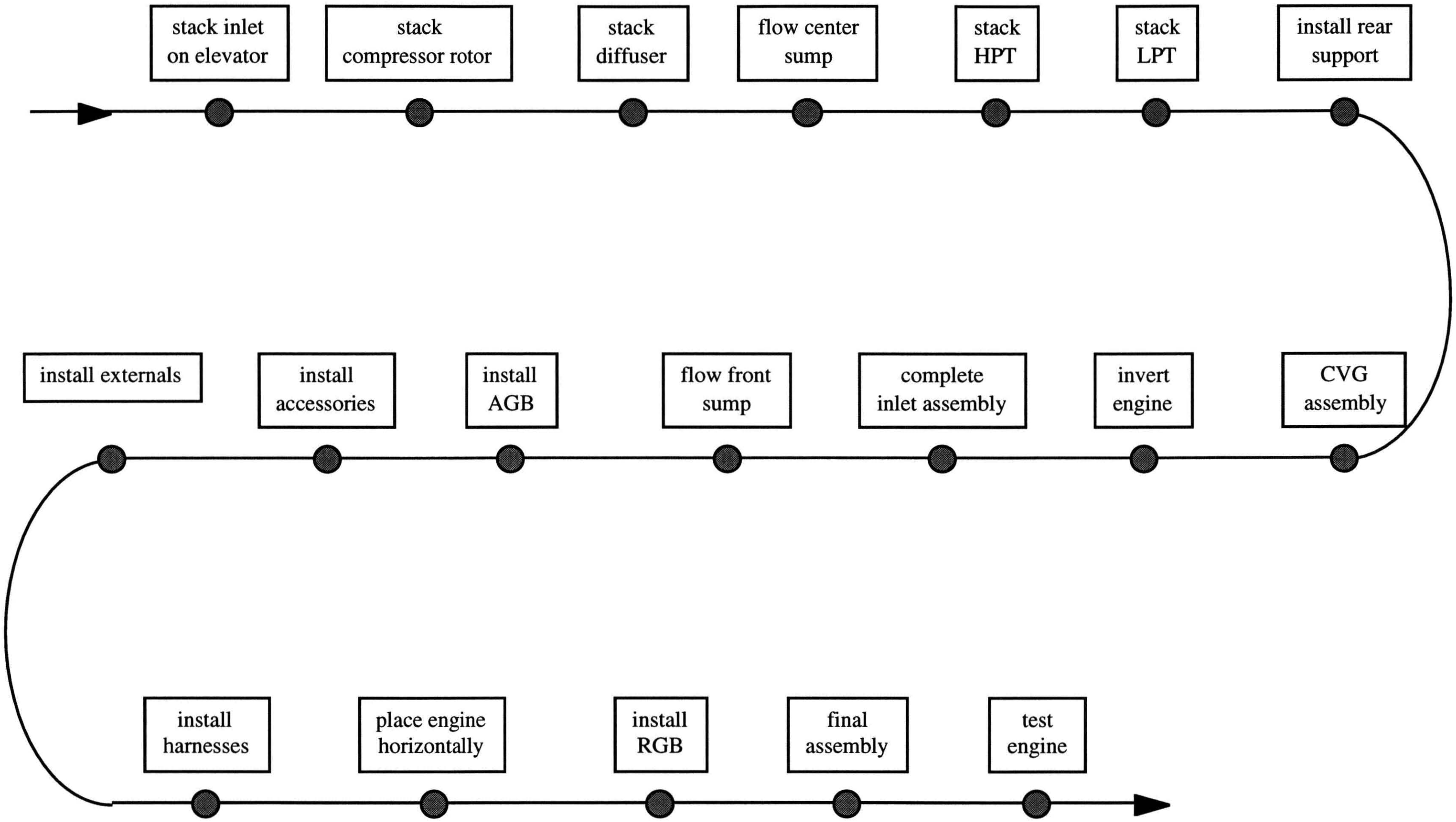
A2
HPT
Parts Storage in MPA
transport to build area
Case and Vanes Build
transport
Parts Storage in MPA
transport
Parts Storage in MPA
transport to build area
1st Stage Build
2nd Stage Build
transport to build area
Rotor and Stator Build
Check Out (with Inspector)
Transport to Vertical
Storage
Distance Traveled: 680’
Inspections:13
Storage
Transportation
Assembly
Inspection



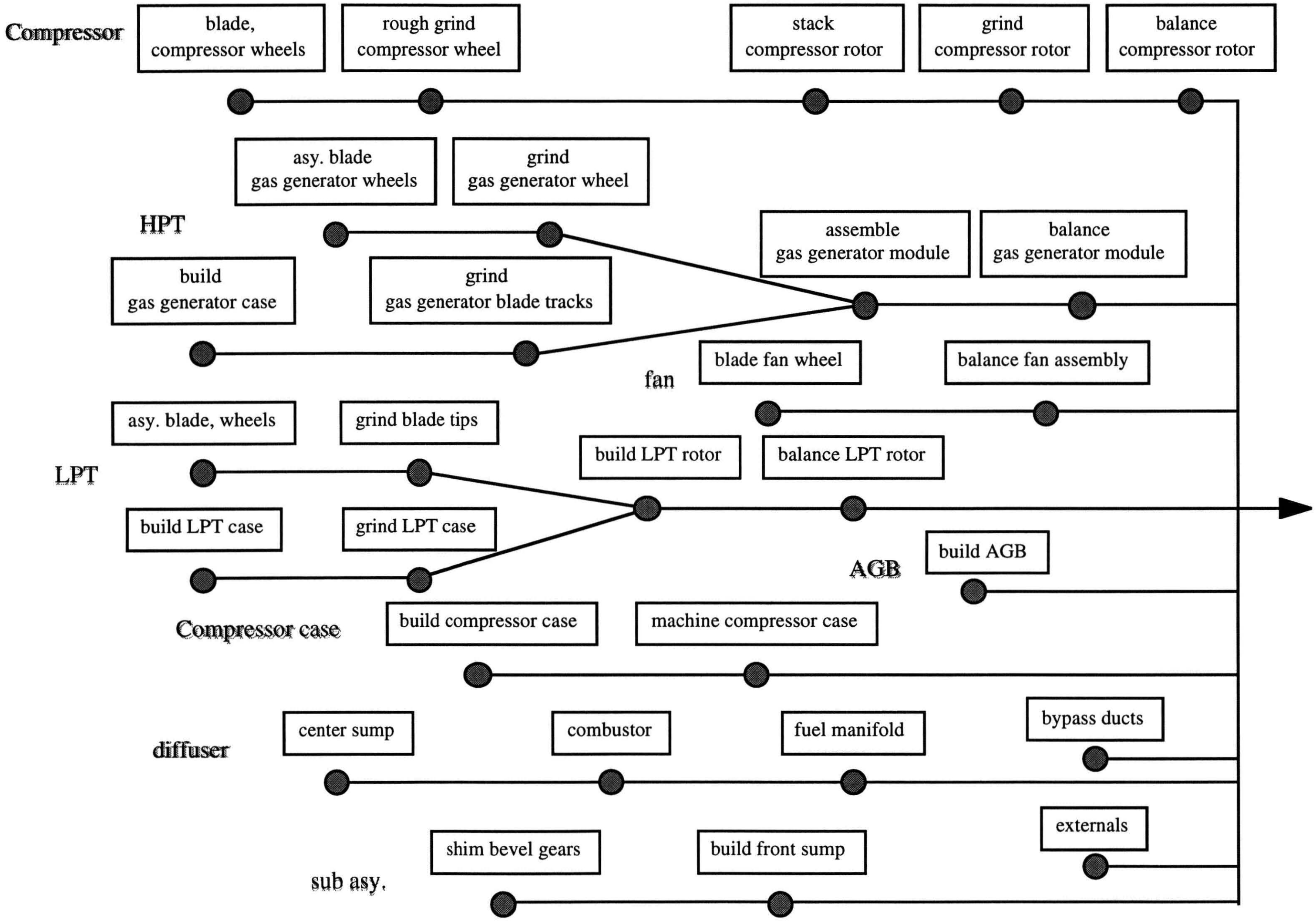
LPT
Parts Storage in MPA
Parts Storage in MPA
transport to build area
transport to build area
3rd Stage Build
4th Stage Build
Parts Storage in MPA
transport
transport
Parts Storage in MPA
transport to build area
6th Stage Build
5th Stage Build
transport to build area
Rotors & Stators
Case Build
Parts Storage in MPA
Parts Storage in MPA
Shaft Build
Install Shaft
3rd Disk Build
transport
transport
Vanes
T/R Airseal
Parts Storage in MPA
Transport to balance machine
Balance
Transport from balance machine
Distance Traveled: 864’
Inspections:36
Transport Turbine Exaust Case From C.J.’s Area (576’)
Install P-flange
Check Out (with Inspector)
Transport to Horizontal
A2
Storage



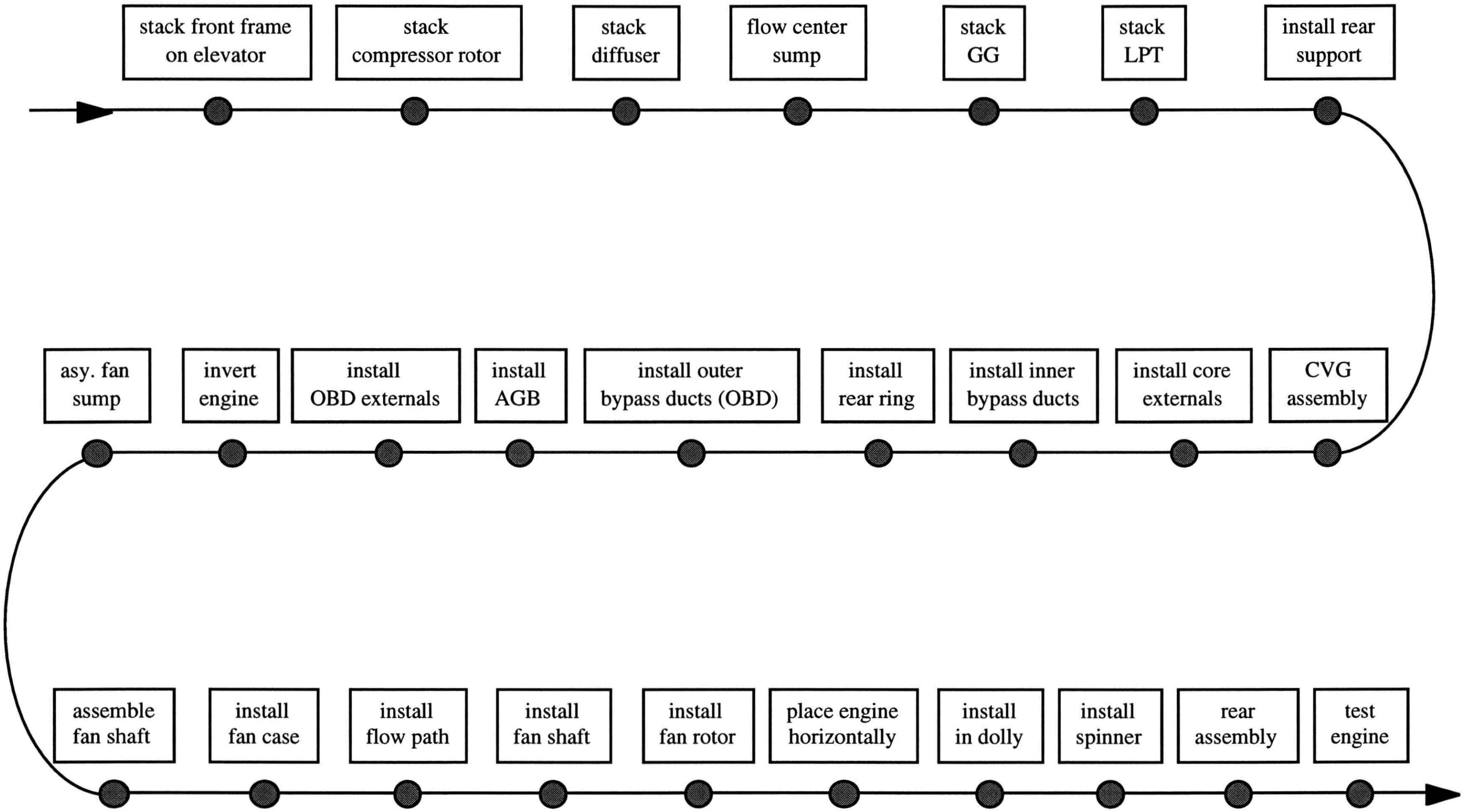
B1 Process Map 1/2



B1 Process Map 2/2

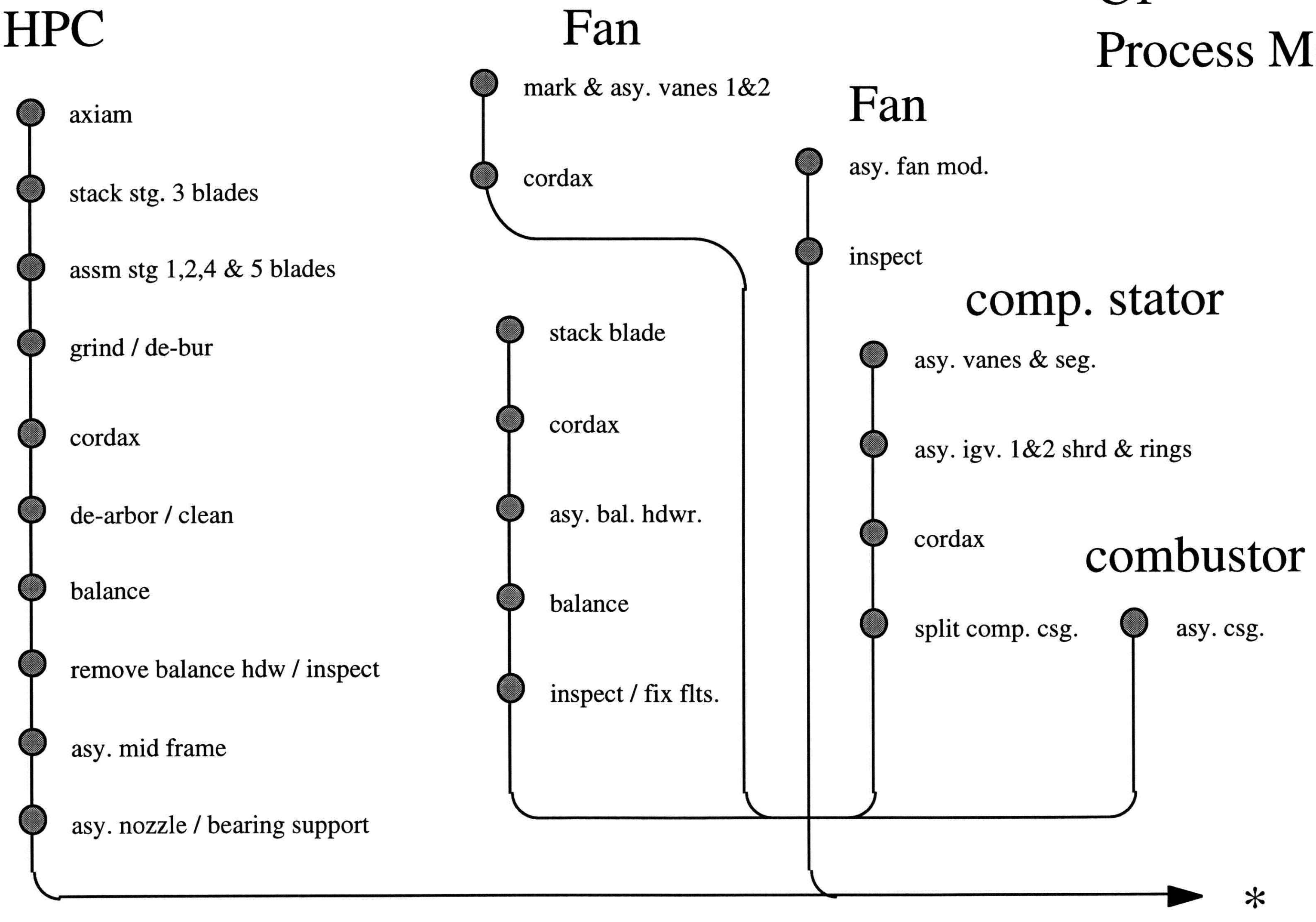


B2 Process Map 1/2



B2 Process Map 2/2

C1
Process Map



HPC

- axiam
- stack stg. 3 blades
- assm stg 1,2,4 & 5 blades
- grind / de-bur
- cordax
- de-arbor / clean
- balance
- remove balance hdw / inspect
- asy. mid frame
- asy. nozzle / bearing support

Fan

- mark & asy. vanes 1&2
- cordax

- stack blade
- cordax
- asy. bal. hdwr.
- balance
- inspect / fix flts.

Fan

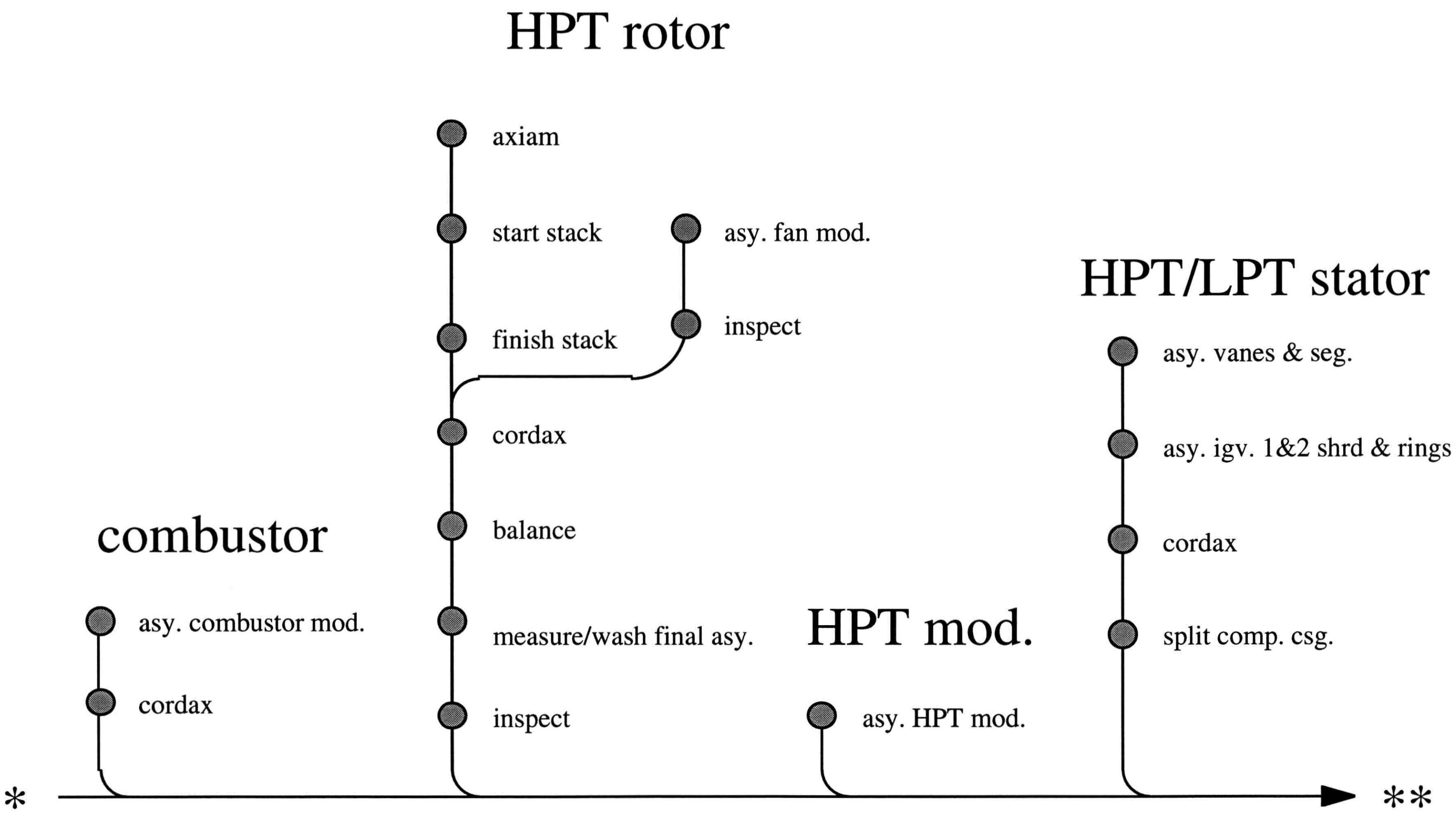
- asy. fan mod.
- inspect

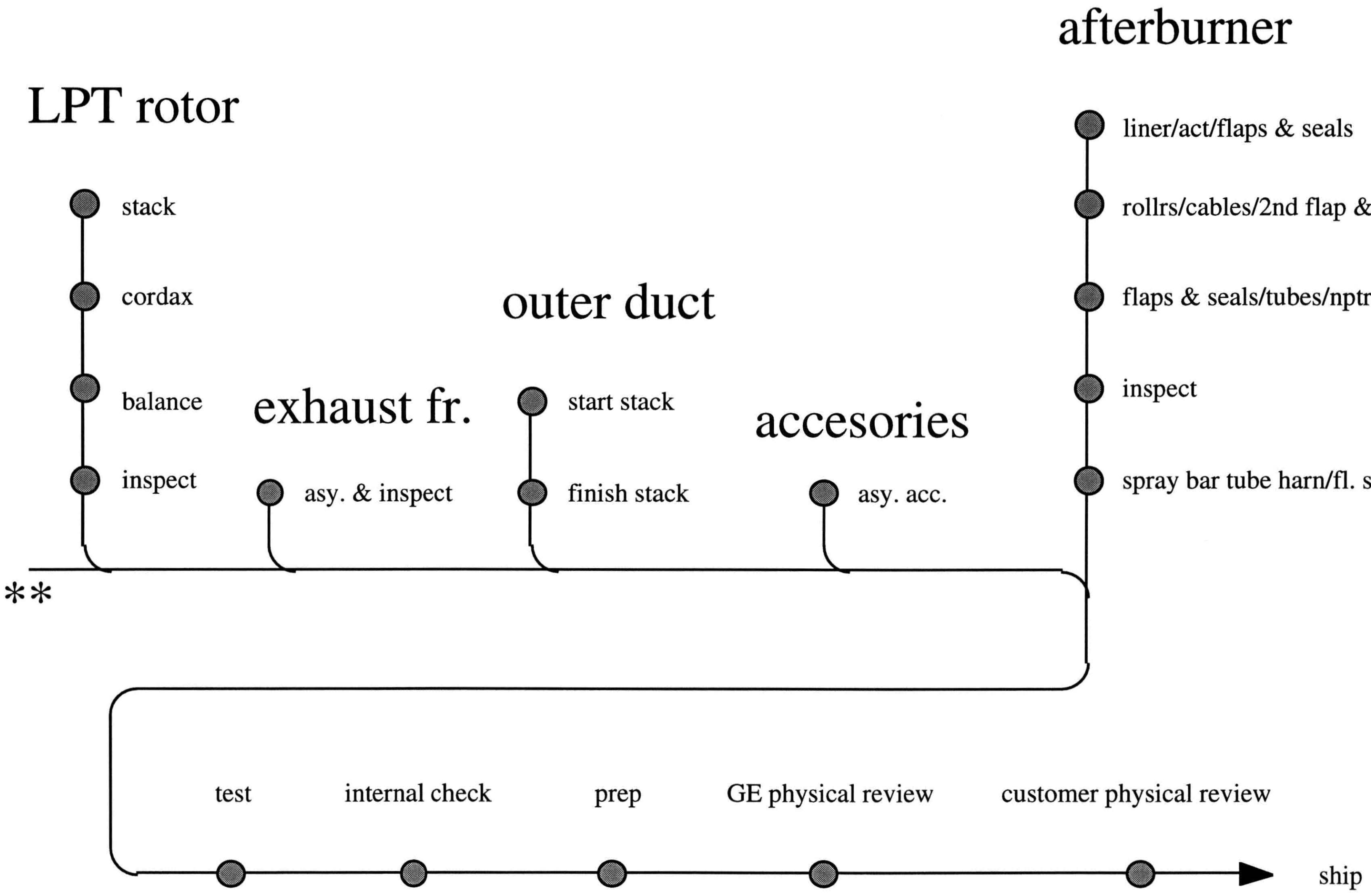
comp. stator

- asy. vanes & seg.
- asy. igv. 1&2 shrd & rings
- cordax
- split comp. csg.

combustor

- asy. csg.


HPT rotor
axiam
start stack
asy. fan mod.
inspect
HPT/LPT stator
finish stack
asy. vanes & seg.
cordax
asy. igv. 1&2 shrd & rings
combustor
balance
cordax
asy. combustor mod.
measure/wash final asy.
HPT mod.
split comp. csg.
cordax
inspect
asy. HPT mod.
*
**



afterburner

LPT rotor

liner/act/flaps & seals

stack

rollrs/cables/2nd flap & seals

cordax

outer duct

flaps & seals/tubes/nptr

balance

exhaust fr.

start stack

inspect

accesories

inspect

asy. & inspect

finish stack

asy. acc.

spray bar tube harn/fl. sensor

**

test

internal check

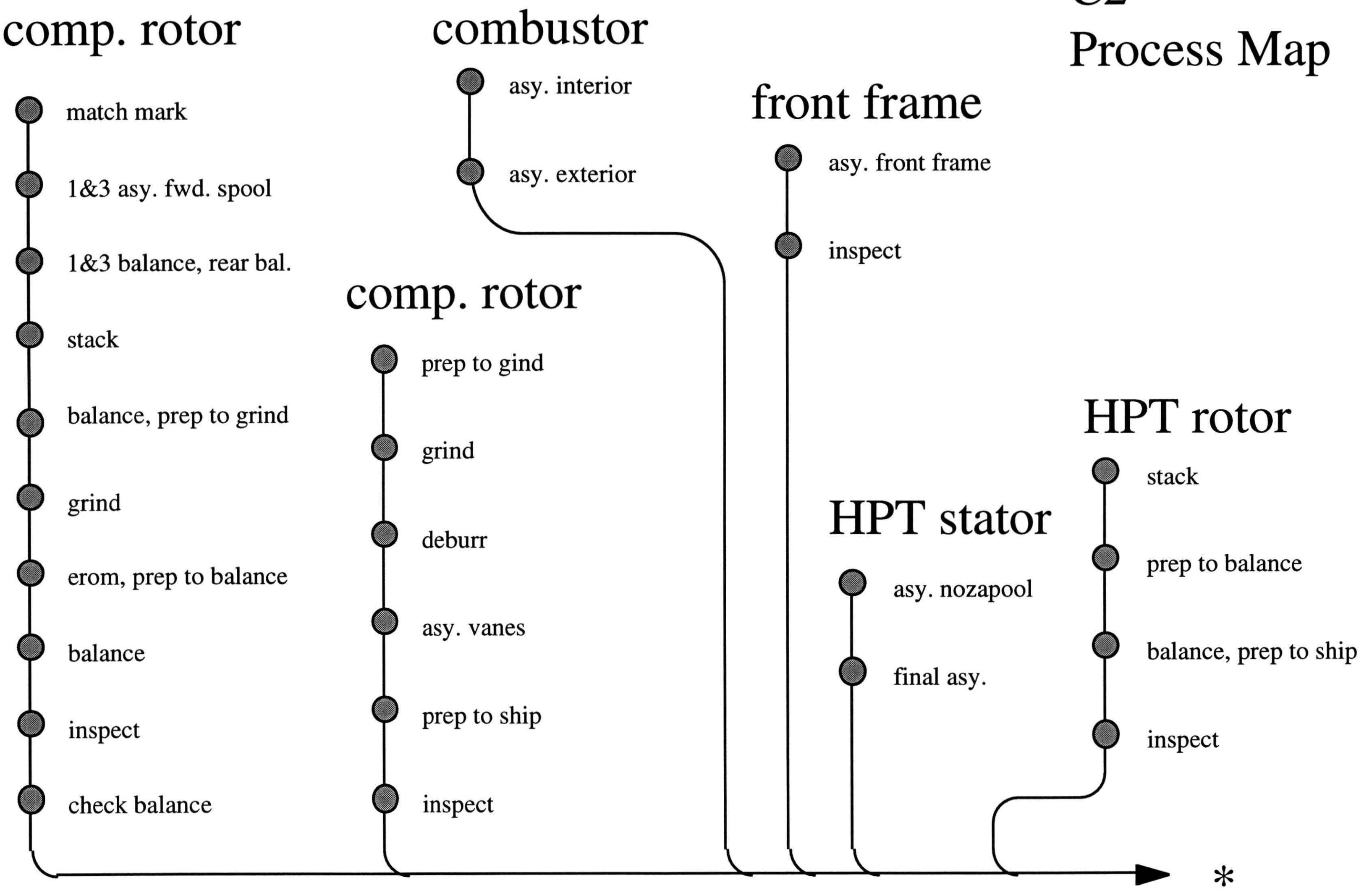
prep

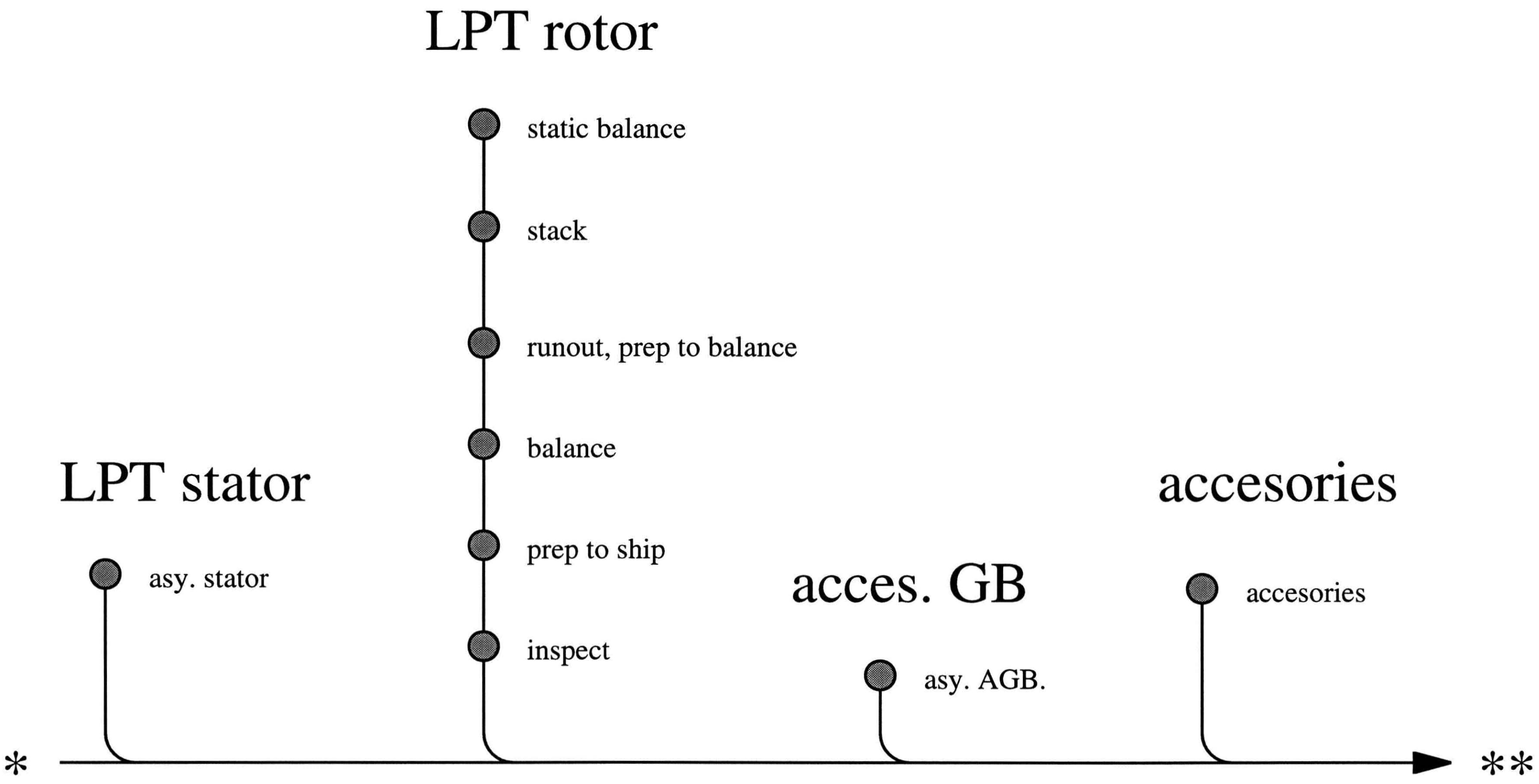
GE physical review

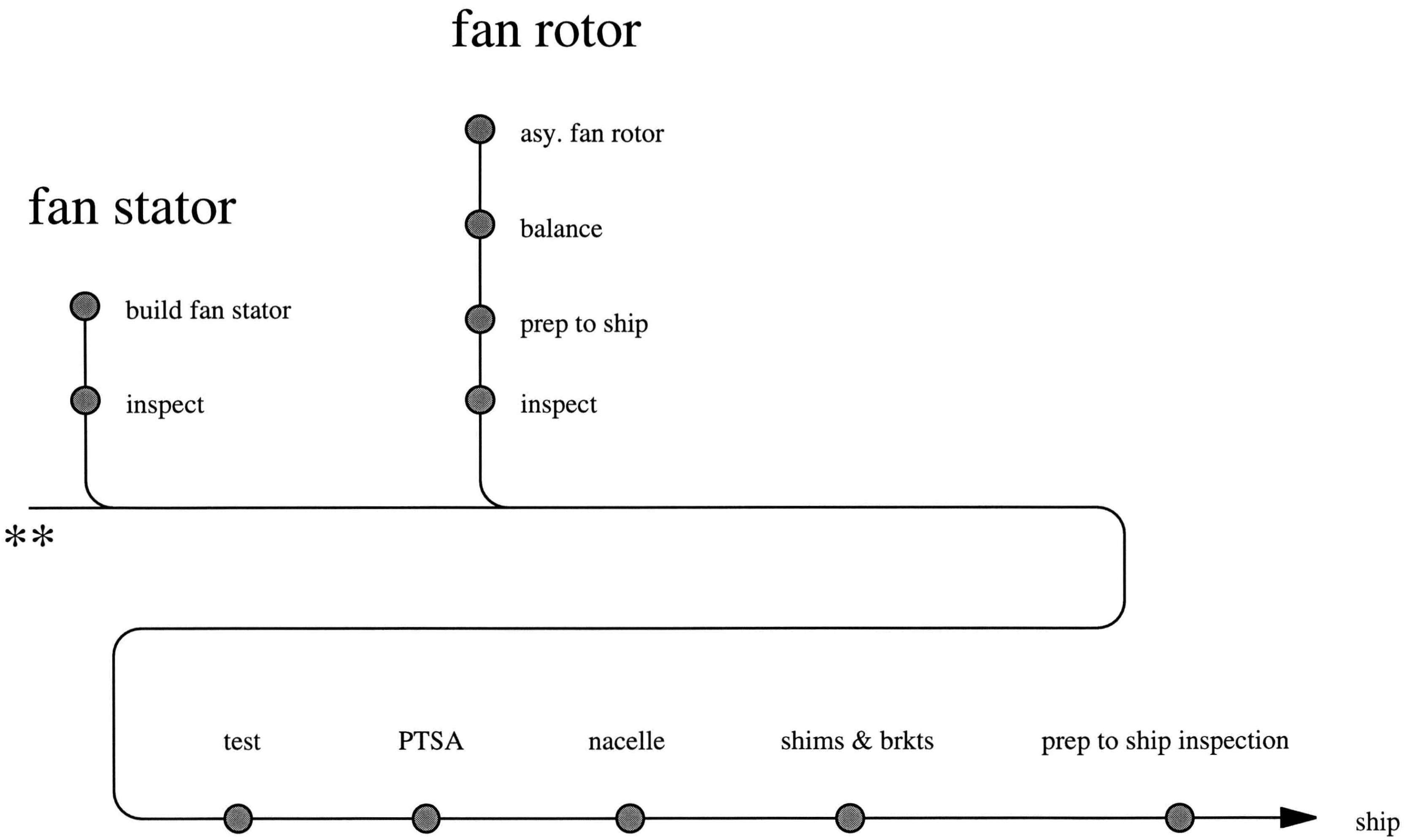
customer physical review

ship

C2
Process Map




LPT rotor
static balance
stack
runout, prep to balance
balance
prep to ship
inspect
LPT stator
asy. stator
acces. GB
asy. AGB.
accesories
accesories
*
**


fan rotor
asy. fan rotor
balance
prep to ship
inspect
fan stator
build fan stator
inspect
**
test
PTSA
nacelle
shims & brkts
prep to ship inspection
ship

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