INTRODUCTION AND GENERAL APPROACH

This paper summarizes a study of rear axles made to determine the feasibility of automating all or part of their final assembly. This is a disguised version of a study made for an automobile manufacturer in the middle 1980s. The automation project was not implemented. The axle is illustrated in Figure 1. The project involved all aspects of assembly, both technical and economic, including:

- Assembly operations
- Assembly system design and floor layout
- Material flow timing and workstation timing
- Robots, tooling, and controls
- Parts handling and conveying
- Interface to management systems
- Investment cost estimates and financial justifications
- Computer simulations, transport studies, and throughput studies
- Suggestions for redesigns to improve automatibility

The project began with a statement of the client's objectives for the product, dealing with model mix, production volume and cost projections, quality issues, and the desire to learn more about assembly automation. The feasibility of automating assembly depends on the product's design and the difficulty of individual part mates. Engineering analyses based on part mating theory were used to predict difficult mates, which often arise from close clearances and tolerance stackups, including robot, jig, and gripper errors. Many alternate assembly sequences were considered, since these alternatives heavily affect final system layout, cost, tolerances, jig and grip surfaces, deployment of people where necessary, and so on. Several redesigns and robot lab experiments were suggested to reduce assembly risk or make several operations feasible for automatic assembly.
Candidate assembly sequences were then paired with possible assembly technologies, including fixed automation, robots and people. These were analyzed by computer simulation and economic justification programs to determine good candidate systems for presentation to the client. Vendors were consulted concerning feasibility and cost for various robots, tools, and transport options. A final list of options and recommendations was presented, along with our recommendations.

**Characteristics of the Rear Axle**

In the case of the rear axle, options for redesign were limited. This is a mature product, well tested in the field. Several options for redesign were generated and remain candidates for future use. These deal with difficult mates that are presently deemed unsuitable for robots or automatic machines: removal and replacement of the shaft pin bolt (SPB) which retains the pinion shaft in the differential, and insertion and coiling of the emergency brake cables. In each case, solution of the problem would involve cooperation with other departments in the plant or with vendors. In the absence of any changes, this study assumed retention of the present design. Figure 2 shows the parts and the assembly constraints. Figure 3 shows the feasible assembly sequences.
Figure 2. Axle Parts and Assembly Constraints
Figure 3. Diagram of Feasible Assembly Sequences
Two other aspects of the product affect the feasibility of automation, namely the accuracy of the parts and the method of presenting them to the assembly system. In several instances, the probability of unsuccessful part mating is increased by parts that are out of tolerance or have missing or damaged chamfers. Several surfaces on axle shafts have such problems, as do the ends of axle tubes. The inside of side gears in the spline area may also be a problem. As is typical in such situations, assembly workers have learned to overcome these problems, but automated systems are not yet that smart. The tooling and part mating recommendations seek to overcome these problems, but it is generally advisable to correct them where they occur.

An additional quality problem concerns split axle tubes. Such splits are discovered at various stages of manufacture, including final pressure test. Since the last places such splits could occur are early in assembly -- either where tubes are joined to the central gear case or during bearing insertion -- we recommended an extra air test just after these operations and before any additional value is added.

Because redesign was not a major feature of this study, the emphasis fell on designing part mating methods, tooling to support part mating, determining assembly sequences, choosing assembly and transport technology options, combining options into assembly systems, designing floor layouts, and analyzing the candidate systems for economic and technical feasibility. A major study point concerned material transport options and part provisioning. AGV's were compared to inverted monorails technically and economically, including counting how many vehicles were needed. For AGV's, both dedicated and taxi modes were simulated. The interface between fabrication and assembly, which occurs at the kitting area, was also examined carefully to determine feasible alternatives. These include structured dunnage ("dunnage" refers to either disposable or reused parts carriers, baskets, boxes, etc.), simple vision systems, and better parts handling in the fabrication areas.

We took as a starting point a preliminary system design and floor layout created by the client. This design was refined as to task definitions and times, using the client's standard time data, and was used as a baseline for comparison to designs the authors generated. All these designs used the same database of candidate task times and equipment costs, even though different assembly sequences and equipment choices were tried.

The candidate systems are similar in most respects to systems we are aware of around the world, although the most ambitious ones undoubtedly were preceded by thorough redesign of the product. The public literature includes information on VW's Hall 54 for automated final car assembly and engine dressing, FIAT's Termoli, Italy engine assembly plant, and recent GM
developments on engine assembly and cockpit installation. At various points, these systems include AGV's, vision systems, tool changing robots, two or three robots at one station, robot-borne cluster head nut runners, a mix of people and automation in the same system, and so on. Completely unmanned assembly is a goal in some cases. This is not readily attained without extensive redesign. The added cost of redesigned parts, if any, must be compared to the expected savings, such as reliability of the system, product quality, cost growth control, and so on.

**Part Mating Issues**

Every part mate involved in axle final assembly was studied. Several involve risky mates, affect possible assembly sequences, or have other impacts on the final assembly system. These include backing plates, axle shafts, bearings, C-washers, and brake drums. Some part quality issues are listed in Table 1. Each operation will be discussed in turn. Figure 4, Figure 5, and Figure 6 summarize the issues in the final recommended assembly sequence.

**Major Parts**

Insertion of bearings, seals and backing plate studs is recommended to be done by fixed automation. These stations will address one axle at a time on a power/free conveyor. To ensure success of these operations, care must be taken to provide the chamfers on the ID of tube ends that show on the print. These chamfers have been observed on many sample tubes to be of a wide range of sizes, including nonexistent. Such stations must be adjusted slightly up or down to accommodate different diameter tubes resting in the same conveyor chocks. Referencing the insertion tool to the top of the tube is a way to do this.
PART QUALITY ISSUES

TOLERANCES:

SHAFT FLANGE RUNOUT W R T SHAFT AXIS
JIGGING POINTS FOR TUBE-CASE ASSEMBLY

INTERMITTENT CHAMFERS:

SHAFT BUTTON
SHAFT HUB
SHAFT C-WASHER GROOVE
TUBE END
BACKING PLATE FLANGE [FINESSES WITH TOOL DESIGN]
PINION SHAFT ENDS [A PROBLEM REGARDLESS OF WHETHER PIN COMES ALL THE WAY OUT OR NOT]

IT IS CRUCIAL TO MAKE PARTS TO PRINT OR TO REVISE PRINTS BEFORE GOING OUT FOR FIRM BID

Table 1 Part Quality

Assembly of backing plates is influenced by presence or absence of a chamfer on the pilot diameter of the flange. A tooling concept is suggested that uses the tube itself as the pilot. (See Figure 7.) The success of this tool depends on an OD chamfer on the end of the tube. The tool concept takes advantage of the fact that the ID of the backing plate is a carefully held dimension. This tool first picks up 4 nuts from 4 feeder slides, then picks up the backing plate by the ID and holds it magnetically. The tool slides over the end of the tube on its OD and pushes on until it butts against the pilot diameter of the flange. The nut runner in the tool advances and forces the backing plate off the magnets and onto the pilot diameter, meanwhile driving the nuts home.

Assembly of axle shafts into tubes is the riskiest part mate. A heavy part must be cantilevered and inserted into a hole so that the tip of the axle will go into a second hole 24" to 36" inside the tube. The gripper must grasp the shaft on the flange face and OD. A tolerance stackup analysis including lateral and angular errors due to robot, jigging, gripping, and both axle and shaft fabrication shows that this mate could fail frequently.

We recommended several alternate shaft insertion strategies. Some involve sensing the location of the shaft tip after it is gripped. Others involve utilizing a two or three phase insertion method in which the shaft is put most of the way in, then released so as to let it fall to a standard stable position in the tube, then regripped for final insertion into the side gear’s spline.
Even if tolerance issues on axle shafts are resolved, successful mating of axles and side gears may require robots on each side to work together, twisting the shafts. This would ensure that there is relative rotation between shaft ends and the gears. People on the line use this strategy now. If it is necessary, it would make infeasible the line layout in the client's baseline system, which had only one robot at each station.

**Brake cables** present serious assembly difficulties. They are awkward, and both ends must be dealt with at different times during assembly. Based on current methods, the cable surrounds the brake drum. The drum must be put on after one end of the cable is installed and before the other end is hooked to a shaft stud. The last operation seems unavoidably manual, forcing one of two alternatives: if brake drum installation is automated, two people are needed at the end of the line just to hook cables to studs; or brake drum installation is manual and the same person hooks the cables. The former leads to poor line balance, so the latter has been chosen even though brake drum insertion is apparently an easy robot task.

If brake cables are inserted into backing plates after the plates are attached to the axle assemblies, then the insertion of brake

<table>
<thead>
<tr>
<th>PART</th>
<th>ASSY METHOD</th>
<th>FEEDING METHOD</th>
<th>GRIP SURFACE</th>
<th>TOLERANCES</th>
<th>NEEDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BACKING PLATE BOLTS, BEARINGS, SEALS, GREASE</td>
<td>ROBOT OR FIXED AUTOMATION (FIXED AUTO PREFERRED)</td>
<td>HOPPER OR BOWL</td>
<td>INSIDE DIAM. TOOL PRESSES ON O.D.</td>
<td>SUM OF CHAMFERS TYP +/- 0.04&quot;-0.06&quot;</td>
<td>THE CHAMFERS, MAYBE A LITTLE LUBE</td>
</tr>
<tr>
<td>BRAKE CABLES</td>
<td>MANUAL</td>
<td>PRECOILED OR LOOSE</td>
<td>AS REQ'D</td>
<td>N/A</td>
<td>AXLE PAN-FACE DOWN</td>
</tr>
<tr>
<td>FIRST AIR TEST</td>
<td>FIXED AUTO</td>
<td>N/A</td>
<td>REGISTER ON PAN FACE &amp; TUBE ENDS</td>
<td>NOT DIFFICULT</td>
<td>CHAMFERS ON TOOL</td>
</tr>
<tr>
<td>BACKING PLATE</td>
<td>ROBOT OR F.A. IMPORTANT FOR CYCLE TIME THAT NUTS BE DRIVEN BY SAME TOOL AT SAME TIME.</td>
<td>KIT ON PALLET. COULD USE STRUCTURED DUNNAGE &amp; VISION TO SKIP KITTING.</td>
<td>ID--ALSO SQUEEZE/ CENTER BRAKE SHOES</td>
<td>CHAMFERS ON TOOL MEET CHAMFERS ON TUBE ENDS</td>
<td>CHAMFERS. ALSO ALIGNMENT OF BOLT HOLES- VISION OR STRUCTURED DUNNAGE</td>
</tr>
</tbody>
</table>

**Figure 4** Part Feeding, Assembly, and Tooling Summary--1
<table>
<thead>
<tr>
<th>PART</th>
<th>ASSY METHOD</th>
<th>FEEDING METHOD</th>
<th>GRIP SURFACE</th>
<th>TOLERANCES</th>
<th>NEEDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AXLE SHAFTS</td>
<td>ROBOT</td>
<td>KIT ON PALLETT. COULD USE STRUCTURED DUNNAGE &amp; VISION TO SKIP KITTING.</td>
<td>FLANGE FACE &amp; FLANGE O.D.</td>
<td>BUTTON CHAMFER TO CASE CHAMFER &gt; POS UNCERTAINTY + AXLE TOLERANCES: LIKELY SOURCE OF TROUBLE! BUTTON CHAMFER IS USUALLY MISSING.</td>
<td>EXPERIMENTS. PROBABLY ASSY METHOD USING A SENSOR OR RE-GRIP AFTER SHAFT IS FAR IN TUBE. PART QUALITY IS AN ISSUE.</td>
</tr>
<tr>
<td>C-WASHERS</td>
<td>PEOPLE OR ROBOT. (PEOPLE PREFERRED)</td>
<td>CURRENT TOOLS COULD USE IMPROVEMENT.</td>
<td>AS DONE NOW</td>
<td>FOR AUTOMATIC ASSY, SLOT CHAMFERS WOULD HELP. A PART QUALITY ISSUE.</td>
<td>LITTLE IF PEOPLE PUT THEM IN.</td>
</tr>
<tr>
<td>SPB AND PINION SHAFT</td>
<td>PEOPLE OR ROBOT. (PEOPLE PREFERRED)</td>
<td>N/A</td>
<td>AS DONE NOW</td>
<td>N/A</td>
<td>A REDESIGN IF ROBOTS WERE DESIRED</td>
</tr>
<tr>
<td>BRAKE DRUMS</td>
<td>PEOPLE, ROBOTS, OR FIXED AUTO. IMPORTANT FOR CYCLE TIME THAT TNN NUT BE PUT ON AT SAME TIME BY SAME TOOL.</td>
<td>KIT ON PALLETT. COULD USE STRUCTURED DUNNAGE &amp; VISION TO SKIP KITTING.</td>
<td>O.D. AND CARRIER SIDE OF RIM.</td>
<td>~ ±0.0625&quot; I.E., NOT DIFFICULT AS LONG AS AXLES REALLY HAVE THEIR CHAMFERS. A PART QUALITY ISSUE.</td>
<td>CHAMFERS ON SHAFT ENDS. COORDINATION WITH ROBOT/TOOL ON OTHER AXLE TO ROTATE TO GET STUDS INTO HOLES.</td>
</tr>
</tbody>
</table>

**Figure 5. Part Feeding, Assembly, and Tooling Summary-2**

Cables is much easier if the axles are oriented pan face down, although they must be pan-face up for several other operations. When we were considering automating C-washer insertion, we thought of designing tooling that would operate from below. A dropped C-washer would fall out harmlessly. Even oil fill could in principle be done with the pan face down if the cover were put on first (again from below) and the drain hole used for fill. While these options have some appeal, they have disadvantages that caused them to be dropped.

Another alternative is to attach cables to backing plates before mating plates to axle assemblies. The client or its vendor could do this. The problem is that the cables dangle awkwardly from the plates and the axle, making automatic handling risky. Cables could snag or could be pinched in fixtures. These problems also exist if we utilize an alternate assembly sequence in which backing plates are installed right after the bearings and seals. These operations can easily occur pan-face down. Backing plate attachment could be manual or automatic, and brake cable installation could occur right after. When the axles are transferred to pallets they could be turned pan-face up and would stay that way throughout the rest of the operations. Pallets that permit axle rotation and people's time to rotate them would not be needed.
In short, additional attention needs to be paid to brake cables, including pre-coiling them and devising a better way to tie off the loose ends prior to painting and shipment to the vehicle assembly plant. Several major advantages would be gained, including redeployment of people away from robots, saving of some people, and avoidance of turning assemblies 180° twice.

<table>
<thead>
<tr>
<th>PART</th>
<th>ASSY METHOD</th>
<th>FEEDING METHOD</th>
<th>GRIP METHOD</th>
<th>TOLERANCES</th>
<th>NEEDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OIL FILL</td>
<td>ROBOT CARRIES FILL TUBE</td>
<td>AS NOW</td>
<td>N/A</td>
<td>NOT DIFFICULT</td>
<td>POSITIVE SHUTOFF AND NOZZLE WIPER TO PREVENT DRIPS SO PANFACE DOES NOT NEED WIPING.</td>
</tr>
<tr>
<td>RTV</td>
<td>ROBOT APPLIES TO PAN FACE OR TO COVER. PAN FACE PREFERRED TO AID BOLT-COVER KITTING.</td>
<td>AS NOW</td>
<td>REGISTER TOOL ON PAN FACE AND TOOLING RECESSES</td>
<td>NOT DIFFICULT</td>
<td>CLEAN PAN FACE</td>
</tr>
<tr>
<td>COVER &amp; BOLTS</td>
<td>ROBOT WITH BOLT DRIVER IN GRIPPER</td>
<td>KIT/FEED BOLTS TO COVER FIRST.</td>
<td>RIM OF COVER REGISTE TOOL ON PAN FACE AND TOOLING RECESSES</td>
<td>~ +/- 0.05&quot; I.E., NOT DIFFICULT</td>
<td>CARE PROGRAMMING ROBOT SO BOLTS DON'T FLOP OUT NOT LIKELY TO BE A PROBLEM.</td>
</tr>
<tr>
<td>RATIO TAG</td>
<td>SIMULT. WITH BOLTS</td>
<td>KIT WITH BOLTS</td>
<td>N/A</td>
<td>SAME AS BOLT</td>
<td>THIS PART IS A PROBLEM. REPLACE WITH LASER MARKING ON CASE.</td>
</tr>
<tr>
<td>FINAL AIR TEST</td>
<td>ROBOT CARRIES TOOL IMPORTANT FOR CYCLE TIME THAT PLUG IS PUT IN BY SAME TOOL RIGHT AFTER TEST.</td>
<td>N/A</td>
<td>SADDLE ON TUBE</td>
<td>NOT DIFFICULT. A LITTLE REDESIGN ON THE PLUG WOULD HELP.</td>
<td>WOULD BE GOOD TO STANDARDIZE TEST HOLE LOCATION ON ALL MODELS.</td>
</tr>
</tbody>
</table>

**Figure 6 Part Feeding, Assembly, and Tooling Summary-3**

Automated insertion of C-washers is probably feasible, but this task, too, is surrounded by manual tasks, namely removal and reinsertion of the SPB. Only replacement of the SPB by another pinion shaft retention method would make automatic C-washer insertion useful. Several redesigns have been suggested, of which the most promising is replacement of the SPB by a roll pin.
Figure 7. Detail of Backing Plate Gripper. The gripper operates in four steps. 1. The gripper holds the backing plate with the magnets while approaching the flange. 2. It advances and lands on the tube flange opening using its own chamfer. 3. The nut runners advance, pushing the backing plate off the tool onto the pilot diameter on the flange. Then they tighten the nuts. 4. The tool leaves.

A lot of additional work would have to be devoted to these matters before suitable alternatives emerged. The reward would be large, however, since, together with brake cables, the C-washer operations account for all of the people that the baseline and recommended systems contain within the robotic part of the line.

The ratio tag is an awkward part, hard to feed, easy to lose. It should be replaced with some other marking method, such as laser barcode marking. As discussed below, the bar code could include model and date/time information and could be used by the production control system to coordinate launching of kits or loading them to pallets.

Other Parts and Tasks
In general, other parts do not present great difficulties. Nuts can be fed down chutes to nut runners while they are in tool storage. Serrated backing plate studs can be similarly fed for automatic insertion into flanges on tubes. Bearings and seals can be magazine fed, packed that way by the vendors. Covers can be stacked for easy robot pickup by magnetic or vacuum grip and turned under a bolt dispenser prior to assembly. C-washers can be fed down chutes for people or automatic tools to pick up magnetically. Air test hole plugs can be bowl fed.

Robotic pickup of kitted shafts, backing plates, and, if applicable, brake drums can be aided by attention to kit tolerances and gripper design. Simple vision systems above pallets or on grippers might be needed to take out gripping uncertainty, or grippers could be designed with wide enough throw and attention to closure motions so that parts are gripped correctly even if they are a bit off location in the kit. Such methods might eventually allow automatic kitting, depending on how much it costs to obtain good structured dunnage.

**Part Quality**

It was noted above that some parts are not made as specified by the prints. This may not affect axle performance but could cause problems for assembly machine vendors. Either the parts should be made to print or else a set of "as built" prints should be prepared for issue to the vendors. This will help ensure that tools, grippers, and fixtures are designed to as accurate specifications as possible, reducing the risk of rework and delay in getting the assembly system operating at full capacity.

From a management point of view, one should strive for the level of quality that the product or the assembly system needs. The assembly system will "inspect" the parts and probably jam on ones that are too far out of tolerance. From an economic point of view, one must remember that the parts presently account for about 93% of an axle's in-plant cost, and final assembly accounts for only about 7%. Efforts to improve part quality could cost too much. Quality for quality's sake is justifiable only on the grounds that a spirit of quality will inevitably result in better axles, even if one cannot precisely trace specific warranty reductions or other benefits to specific investments. A spirit of quality could eliminate many poor practices that management could be unaware of.

**Summary of Part Mating Issues**

Installation of backing plates, brake cables, and the C-washers confronted us with several assembly sequence and automation problems. These were resolved via line balancing and technical judgment: people would do the difficult operations.
Installation of axle shafts, backing plates, and brake drums present some risks associated with part quality. Experiments were recommended to reduce these risks, and specific part quality improvements were recommended.

**Tooling, Jigs, Fixtures, and Workstations**

This section covers design of pallets, kits, and robot workstations. These designs require a decision as to how many axles will be on a pallet. Later discussions will justify a choice of 4 axles per pallet, based on economics and system timing.

Pallet design must conform to access needs of people, robots, and kits. For economy, one pallet design should be used for all axle models. A suitable design places the axles on about 33" centers, leaving about 17" for a walk-in space to help a person reach the differential. See Figure 8. If longer pallets are used to create more space between axles, rotational type robots will have difficulty reaching all 4 axles to insert shafts. (Typical robots in this class include the Cincinnati Milacron T3 767 or the GMF S 360R, each with about 100" reach and 150# payload. KUKA, ASEA, and Toshiba make similar robots.) If space for people is a problem, the robot can be mounted on a linear axis along side the pallet at an extra cost of $20K to $30K and about 3 seconds per move. Then a longer pallet can be used.

Other access difficulties arise because of the unusable space around the center of the robot. The latter has typically a 36" to 45" radius. The unusable space problem is not solved by mounting the robot upside down. It is eased, however, by using the powered linear axis parallel to the pallet.

Only one rotational robot could be found that could insert axle shafts and also reach the differentials with 4 axles per pallet. For assembly sequence and throughput reasons, however, no systems were designed that combined end-of-tube and center-of-axle operations at the same station.

An alternative to rotational robots would be gantries. Their reach is essentially unlimited. However, they are typically about twice as expensive as rotational robots. They were recommended only where their reach is essential.

We recommended that all reach estimates be confirmed by full-scale 3 dimensional CAD simulations or actual mockups. The above studies used scale 2 dimensional CAD based on manufacturers' drawings of reachable regions in their literature. Such regions may shrink when different wrist axis position combinations are used. Somewhat contorted configurations may occur while putting in axles or backing plates. Only the Cincinnati Milacron "3 roll wrist" may be
immune to such problems. See Figure 9 for a typical robot reach analysis, of which about 25 were done for this study.

Figure 8. Assembly Pallet with Four Axles on It.

The speed and repeatability of suitable rotational robots appears adequate for the axle's tasks. Typical GMF S 360R task times, observed from video tapes at conferences, support our assumption of a 15 second cycle time, plus about 3 seconds to reach from one axle to the next on the pallet. A 15 second tool change time allowance is probably more than enough, especially if tools are centrally located near the pallet. Experiments to verify task times are particularly important because so much of the system design depends on timing and line balance.
These robots have about 0.02"–0.05" repeatability. To avoid oscillations when carrying heavy tools and parts, they cannot be run at full speed. Better dynamic control algorithms are needed. Repeatability itself may or may not be payload or warm-up dependent. Experiments are needed to determine this. To compensate for repeatability and other errors (jigging, part fabrication, gripping), chamfers must be provided on grippers, grip surfaces of parts, and the entry faces of mating parts. These chamfers must sum to dimensions larger than the largest of contemplated errors. Chamfer sums exceeding twice the RMS error would provide good reliability, although space on some parts and tools of the axle, particularly the backing plate, do not permit this luxury. To reduce contact forces during mating in the presence of error, it was recommended that tools contain engineered compliances such as Remote Center Compliances.

In the recommended system, the axles must be turned over 180°. It was assumed that pallets could be designed to permit this. An additional requirement is that one pallet do for all axle models. A design that permits this involves placing the axle

Figure 9. Reach Analysis for an ASEA Robot and Pallet with Four Axles
tubes on chocks so that the turned center countersink on the input drive shaft is in the same XY location (parallel to the pallet surface) for all models. This center may be accessed by a center point that is spring loaded in the Z (vertical) direction.

Because different axles have different tube diameters, the above design will place the tube centerlines at different heights with respect to the pallet. It is assumed that robot programs can be adjusted automatically to compensate for this. (Other, larger program changes must be made as well, such as to accommodate different tube and shaft lengths.) It was assumed that pallets would have machine-readable codes on them that signal the robot as to which program to use.

In our design, a parts kit would contain the axle shafts, backing plates, and brake drums for one axle assembly. It appears feasible to mount a kit of parts for each axle right next to and below it on the pallet. Kits would be approximately 6' long by 14" wide, and would go on the pallet before the axles do. To conserve space, brake drums and backing plates could be mounted upright rather than flat. This approach contrasts to the client's baseline, in which a kit contained parts for 4 axles, and was placed on top of the pallet after axles were loaded. This sequence requires the kit dunnage to be removed part way through assembly, requiring an extra robot. See Figure 10 for possible layouts of kits on the work pallet.

All other parts are kitted or supplied in bulk to the line at the point where they are used. This includes fasteners, covers, bearings, seals, grease, RTV, and brake cables. Delivery could be via lift truck, AGV's or special pallets that pass through the assembly stations untouched.
Figure 10. Options for Kitting Parts
Assembly System Design

Assembly system design has six main aspects: capacity planning, equipment choice, assignment of tasks to equipment, transport choice, floor layout, and kitting. These interact heavily, and there are many alternatives. We identified several cases worth studying deeply. Computer synthesis, analysis, and simulation tools played a large role in the design. Table 2 lists the alternatives studied.

Capacity Planning

Two choices for production rate were available, 140 hours/week as specified by the client’s baseline system, and 88 hours/week. The former requires 10 hour rolling shifts by the employees, who find themselves with "weekends" in the middle of some weeks. They also work both daytime and nighttime in the course of a three-week period. Current labor agreements provide substantial wage supplements for time over 8 hours per day, time over 40 hours per week, and weekend time. Average employee cost per hour is $26 vs. $24 for 88 hours per week. This wage difference is largely responsible for the ultimate conclusion that 88 hour/wk systems are usually more economical. This conclusion survives the fact that more equipment is needed for most of the 88 hour/wk systems to support their higher production rate. As this conclusion began to emerge, we curtailed study of 140 hour/wk systems; economic analyses were conducted on both, but only 88 hour/wk systems were simulated in detail.

Capacity is influenced by several factors:

- the speed of individual workstations
- time lost while robots change tools
- time lost while people or robots shift attention from one axle on a pallet to the next
- time lost shifting from one pallet to another or waiting while transport takes a pallet away and brings another

Robot tool changing is needed only if a robot is given more than one task and different tools are needed for some of them. Shifting from one axle to another arises if several axles are on a pallet vs. only one. Finally, time is lost shifting between pallets due to their size; lost time can be reduced by double-buffering pallets at stations, although this requires purchase of additional pallets. Transport type also affects pallet shift time, with AGV’s assumed to be slower than conveyors unless double buffering is used. (Double buffering involves providing two work locations for a robot; the robot works at one while transport brings a new pallet to the other. This technique works well for stations with one robot but is almost impossible to arrange at stations with one robot on each
side of a work area. Two robots may be needed for cooperative work to mate axle shafts, for example.)

Two basic system configuration options were studied, serial and parallel. Serial systems represent the extreme in division of labor and efficiency. Each workstation does one task before passing the work to the next station. The parallel configuration gives several jobs to one station. Such a station could have one or more people, or one or more robots. The multiple jobs can be in the form of several steps on one product unit, several product units within reach at once, or both. The time penalties cited above apply: tool change and shifting from job to job.

Long ago it was shown at Ford that the most productive manual assembly line has maximum division of labor and a moving conveyor that brings work to the employees. The moving line turned out to be about 2.5 times more productive at the time (1913) than the team assembly approach it replaced.

However, there are large benefits to be gained from giving several jobs to one person, including pride of workmanship.

<table>
<thead>
<tr>
<th>Configuration Name</th>
<th>Parallel</th>
<th>Serial</th>
<th>Kit Before Load</th>
<th>Kit After Load</th>
<th>4 Axles/Pallet</th>
<th>2 Axles/Pallet</th>
<th>Fixed Install Seals</th>
<th>Robotic Seals</th>
<th>Manual Brake Drum</th>
<th>Auto Brake Drum</th>
<th>Manual C-Washers</th>
<th>Auto C-Washers</th>
<th>Manual Load of MHS</th>
<th>Auto Load of MHS</th>
<th>Air Test Early</th>
<th>Air Test Late</th>
<th>Modeling (S,E,F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client’s Original Proposal</td>
<td>■</td>
<td>○</td>
<td>●</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
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Table 2. Assembly System Options Studied

* S=SIMULATED, E=ECONOMIC ANALYSIS, F=FLOOR PLAN
** DOES NOT INCLUDE BRAKE CABLE OR SPB REMOVAL OPERATIONS
Automated systems also benefit from having several jobs at one station. As with manual systems so arranged, it usually requires several identical stations in parallel to meet the needed production rate. A system with several parallel stations is on average likely to be more resistant to breakdowns, since production can continue when one station is down. A serial line with one job per station is quite vulnerable to breakdowns unless there are buffers between stations. Since station times are short in assembly systems, buffers large enough to provide significant breakdown protection (say 30 minutes’ work) would be very large.

Another advantage to parallel automated systems is that their capacity can be increased incrementally by adding stations one at a time. By contrast, serial systems’ capacity can be increased only by duplicating the entire system. In this regard, parallel systems are more flexible.

A second choice related to the above discussion concerns the number of axles per pallet. We considered quantities from 1 to 4 and decided on 4, as in the client's original design. Several axles per pallet has the beneficial effect of spreading over several axles the lost time due to tool changes and shifting pallets in and out of the station. More than 4 per pallet could cause robot reach problems, while less causes too much time to be lost due to shifting pallets in/out of stations and to tool changes. Full scale computer analyses were required to come to these conclusions.

The result of choosing both a parallel structure and 4 axles per pallet is that we gain the benefits of increased reliability and pride of workmanship while reducing the effects of lost time penalties.

**Equipment Choice and Task Assignment**

These two aspects of system design are discussed together because the computer algorithms used do both at once in an optimal way that meets the required production volume while minimizing annualized cost per axle. Equipment choice required preparation of a database containing candidate "equipment" (people, robots, or fixed automation), giving purchase cost, operating cost, operating speed, need for human supervision, and other economic data. For each assembly step, candidates were listed, including estimated task time. The engineer's judgment is required when deciding which equipment types are suitable candidates for each task, as well as when estimating task times.

The computer calculates production rate while allowing for necessary tool changes and dead time while pallets are shifted in and out. An overall system uptime factor (typically 90% in this study) is also used to allow for failures. The program
allows for different numbers of axles per pallet by allocating in/out time equally over all the axles on a pallet.

In this study, 15 seconds were allowed for a tool change. It was assumed that an AGV would require 30 seconds to remove a pallet while another AGV brought in a new one. An inverted monorail conveyor was assumed able to do this in 10 seconds. If pallets are double-buffered at a robot station, then pallet in/out time was assumed to be 3 seconds. Choosing 4 axles per pallet greatly reduced the differences between these times.

**Choice of Transport Method**

Two types of transport were investigated: AGV's and inverted monorails. Each is capable of switching pallets between destinations, converging several routes to one, electronic control, and rip-out and rerouting with substantial salvage of existing equipment. Each has about the same top speed, and each can carry a pallet of 4 axles.

The cost structures of these types of transport are quite different. The cost of inverted monorails for axle assembly is estimated to be 90% to 95% in the conveyor rails themselves, based on a cost figure given us by Jervis-Webb. ($600-$800 per running foot) Vehicles are so inexpensive ($2000 for power-free and $5000 for self powered) that doubling their number to support buffering does not seriously affect the system's final cost. Tracks appear to be modular and can be reused as long as they are not placed below the main floor level. Reuse would be especially easy if self-powered vehicles were used since there would be no drive chain to resize and restring.

On the other hand, the cost of an AGV system for axles is dominated by the vehicles, at 70%, vs. route-related costs of software, system integration, and guideway at about 25%. (Based on an estimate provided by Eaton Kenway, using the same floor plan as Jervis Webb used.) The vehicles could be reused if the route were changed, but the route costs would have to be paid again. Figure 11 compares these cost structures.
THE AGV AND CONVEYOR SYSTEMS EACH
HAVE 40 VEHICLES & 2500’ OF PATH

$M

AGV SYSTEM

INVERTED MONORAIL SYSTEM

NEW AGV ROUTE

NEW CONVEYOR ROUTE

(SALVAGE TRACK: ASSUME NOT BURIED IN FLOOR)

Figure 11. AGV and Inverted Monorail Cost Comparisons

On a cost basis, inverted monorails look better even after a complete route change. AGV’s have the advantage that they leave the factory floor clear. An inverted monorail could be set below the floor but this would raise its cost as well as the cost of rerouting.

The floor plans of the systems we studied show that some configurations have 1.8 to 2 times more length of transport route or track than others. This is due to the need to provide for access to each of several parallel stations or to provide for double buffering. A simple serial system had the shortest route length. Since the cost structure of conveyors is route-length dominated, conveyors look best with the simple serial system. Even so, using conveyors in parallel systems is still better in overall cost than using AGV’s in the systems we studied.

If AGV’s were chosen, two issues would emerge: how to charge their batteries, and how to dispatch them to pallets that need transport. AGV’s originally found use in warehouses and flexible machining systems (FMS’s). In both of these environments, the station times are long, sometimes an hour. Vehicles often have time to wait at one spot, where charging contacts could be located. This is called opportunity charging.
and permits AGV's to go many hours before a full charge is needed. Usually, however, even AGV's with opportunity charging will need a lengthy charge after 8 hours. In addition, charging usually takes longer than 8 hours, and a long cooling period is also needed. Thus multishift AGV operation presents several operational problems.

Long station times also permit the AGV to leave the pallet and go elsewhere and pick up another. This is called the taxi mode of dispatching. Taxi mode is advantageous because fewer AGV's are needed, saving large amounts of money.

If station times are about the same length as or shorter than the time needed to travel from one station to another, then it makes more sense to keep AGV's assigned to pallets; this is called dedicated mode. Furthermore, if station times are short, there is not much time for opportunity charging.

Putting all this together, we found that short station times lead to two disadvantages: lack of opportunity charging and need for more AGV's. If AGV's were selected, there would be an additional reason to use a parallel system structure and put many jobs at one station.

The alternative to charging is to change batteries. Extra batteries must be purchased, but they are relatively inexpensive and changing time is only about 5 minutes. This appears to be the way to solve the charging problem. Physical storage space would be needed for battery packs, and some people would be needed to manage changing, battery storage, and charging.

Simulations were performed to determine whether taxi mode could be used and to find out how many vehicles would be needed. Typically, taxi mode needs 8% fewer AGV's for a serial system (station times are short) and 35% fewer for the parallel systems we studied, compared to dedicated mode.

**Floor Layout**

Floor layout is affected by the assembly sequence, serial/parallel structure of the system, size of pallets and equipment, safety zones, and the need to recirculate pallets, transport vehicles, and kit dunnage. If taxi mode is used for AGV's, then the efficiency of dispatching and the speed with which a vehicle can respond are increased if extra pathways are provided.

All the floor layouts we made were laid out in scale via CAD. Robot reach areas were taken from manufacturers' literature. Each layout avoids pathways that cross. At the entry of each system is a manually operated transfer hoist. This hoist takes in axles from storage racks that buffer the output of the tube-
case welding machines and puts them on a step conveyor. Along this conveyor are stations where backing plate bolts, bearings, seals and grease are installed, and the assembly is air tested. A rework area is provided nearby. Axles are then automatically loaded onto kitted pallets to make loads of 4.

If the system is serial, the pallet goes through a series of stations that add backing plates and shafts. The pallet then is switched to one of several parallel manual stations where indiffential and brake drum operations are done. Pallets then go to a second serial line for the final operations, after which the axles are transferred to the paint system transporter automatically. Empty pallets return to the kit loading area where empty kits are removed and full ones are put on.

If the system is parallel, then the above pattern is different in that a pallet is directed to one of several parallel robot stations at the beginning of the line and again at the end. The manual region in the middle of the system is always parallel.

**Kitting and Parts Presentation**

The interface between work pallets and the kitting area is a gantry robot that can choose among several kit types. This robot gets its information from sensors on the fixed automation step conveyor; the sensors can read the type of axle using bar codes laser-written onto carrier castings. Kitting is done on demand, that is, by Just-In-Time. Kit builders fill whatever kind of empty kit approaches them. These can be color coded, for example.

The only requirement for smooth operation of such a scheme is that the kit transfer gantry needs buffers of full kits of each kind in sufficient numbers. While this number has not been determined analytically or by simulation, it would not exceed the number of kits that would be in the assembly system at one time, and would equal that number only if that model axle were not being made and no kits for it were in the system. If access to different model axles in the welding machine’s output buffer is easy, then this system can build axles in lots of one; however, lots of 4 (one pallet load) is the recommended minimum.

Recall that, in our design, kits contain the parts for one axle. This means that the space required to store 4 kits is much less than the space required for one pallet. This decision greatly reduces the size of the kit output buffer. To save time kitting the pallets, the gantry robot will pick up 4 kits at once from an escapement at the end of the buffer track.

While this scheme appears workable, there are disadvantages to kitting as a method of parts presentation in assembly. In principle, it represents double handling of parts, and should
be avoided if possible. One may ask, if people make kits, why don't they just do the assembly? One answer is that kitting is likely to be more efficient than assembly since putting a part in a kit may be done without high standards or accompanying inspections. Such a method is most effective for small parts that will not be damaged in the process and which a person can carry many of at a time. Large parts present the opposite picture, and walking time could dominate assembly or kitting time. Thus there are certain negative aspects to kitting axle parts.

Kitting also represents the fact that material handling has not been integrated between fabrication and assembly departments, and part dunnage does not hold parts in repeatable ways. Thus the manual kitting area may be said to be the interface between the assembly system of the future and the fabrication system of the past, regardless of how modern the fabrication machines are.

In the future, more integrated factories likely will not contain manual kitting areas. In their place could be two types of arrangements. One would be a robotic transfer system in which kits are made automatically. Part dunnage would be of sufficient dimensional quality that the robot could find each part with at most the help of a simple vision system. The other arrangement, more suitable for smaller parts, would consist of delivering pallets of such parts directly to the assembly stations where they will be used. Repalletizing (double handling by robot) is thus avoided. However, such bulk supplies of large parts at workstations would take too much space.

In the case of axles, it may be best to take the cost penalties of kitting with the knowledge that it is temporary, and that better ways can be substituted in the future without upsetting the rest of the system.

**Summary of Assembly Equipment**

The recommended assembly system floor layout is shown in Figure 12. This system can produce 1.33 million axles per year operating 88 hours per week. Its equipment and operating assumptions are as follows:

1. At the entry to the system is a manually operated transfer arm or hoist capable of lifting one axle assembly onto a step conveyor.

2. The step conveyor capacity is 338 axles per hour, one axle per conveyor position. Any convenient spacing between axles may be chosen, compatible with the equipment arrayed along this line, which is about 100 ft long.
3. Equipment along this line consists of fixed automation stations that feed and install backing plate studs, bearings, seals, and grease, followed by a station that closes off tube ends, pressure test hole and pan face in order to do an air leak test. A repair line is provided to one side for axles that fail this test.

4. At the end of the main step conveyor is a gantry robot with about 200# payload that can transfer axles to pallets carried by AGV's or by an inverted monorail conveyor. The robot needs 3 degrees of freedom (XYZ).

5. Pallets receive kits prior to arriving at the axle-loading gantry. Kits are loaded 4 at a time from the kitting area's output buffer by another similar gantry. This gantry needs 4 degrees of freedom (XYZ and rotation about the Z or vertical axis) and about 100# payload capacity. Each kit contains two each of axles, backing plates, and brake drums. The first two part types must be held accurately enough for robot grippers to grasp them with 0.005" repeatability. Grippers, part grip surfaces, and gripper approach directions must be designed to achieve these tolerances. It should not be necessary to design the pallets or kits to these tolerances.

6. Pallet loads travel to one of 5 robot stations in Auto Line #1 where backing plates and axles shafts are inserted. Each station has two identical robots: 6 degrees of freedom and about 80# payload. Each robot must change tools. One tool is a 4-spindle nut runner combined with a gripper for backing plate insertion. Nuts are to be fed to escapements from which the tool can pick them up 4 at a time, or 16 at a time if this can be devised. The tool must contain sensors to detect that nut runners are advancing and that correct torque and full advance have been achieved. The robot gets the tool, obtains nuts, then a backing plate, then installs them in one move. This process is repeated 4 times. Then the robot changes to a shaft gripper and installs the shafts. As discussed above, this will be a complex insertion involving several steps and sensors. During the time while the pallet is moving out and a new one is coming in, the robot puts down the shaft gripper and picks up the backing plate gripper. If feasible, the storage place for the backing plate gripper may contain the nut escapement, so that the first set of nuts can be inserted during the time the tool is in storage. The escapement must contain sensors for presence of nuts.

7. Pallets then go to one of 10 manual stations where all the in-differential operations are done and brake drums are installed. Brake cables are also installed at this point and hooked to axle studs after the brake drums go on.

8. The next stop is at a single station where kitted covers are received. A machine puts the bolts (and ratio tag if no alternative is used) in each cover. A robot with 6 degrees of
freedom and 20# payload capacity is used to transfer covers from this machine to the pallet.

9. Last the pallet visits one of 8 single-robot stations in Auto Line #2 where the last operations are done: oil fill, RTV, cover installation, pressure test, and test plug installation. Robots with 6 degrees of freedom and 60# payload are needed. The bolt-driver tool needs bolt advance and torque sensors.

10. Pallets are lifted off the transporter and transferred to another transport system that takes them to the paint shop. Transfer is done by a gantry like the one at the entry to the system: a gantry robot with 1000# payload (if four axles are lifted at once) and XYZ degrees of freedom.

If inverted monorails are used for transport, then 36 transport vehicles will be in the system at any one time. If AGV’s are used in taxi mode, then 19 of them are needed, whereas in dedicated mode 36 are needed. These figures include vehicles in return paths, in battery changing stations, and 10% spares. In any case, 36 pallets will be active in the system at any time.

All robot tool sockets require tool presence/absence sensors. Insertion force overload sensors are also required.

The combination of the listed sensors and the recommended bar codes on carrier castings form the basis for extensive data gathering on system performance. Cycle times, downtimes, forces and torques, and statistical quality control data can be gathered and charted easily. These charts will provide new insight into sources of efficiency and quality.
Figure 12. Recommended Assembly System Floor Layout
**Economic Analysis**

Economic analyses were carried out on several of the candidate assembly system designs to determine their rates of return. The current manual system was analyzed to obtain a reference cost. Based on data provided by the client, we estimated a variable cost per unit of $6.22.

**Method**

Our economic analysis recognized three cost elements: labor, assembly system equipment, and transport system equipment. Labor includes assemblers and kit builders. Each kind of equipment has allocated to it a purchase cost and an operating rate, and within the operating rate are some labor costs for supervision and maintenance. The cost of pallets is also included in equipment cost estimates. If parallel work stations are used, then the cost of replicated tools and other resources is also taken into account.

The rate of return is calculated by calculating a stream of savings and using those savings to pay back the equipment investment.

Taking shift and overtime wage differentials into account, we have the following effective hourly labor costs:

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The estimated cost of a piece of equipment in an automated system also includes an estimate for engineering support for design, installation, debugging, and any other expense over and above raw purchase cost. This support cost is represented by a factor we call "rho." A value for rho of 1.5 indicates that 50% over the purchase cost must be added for support. In our analyses, we used rho = 1.2 for a manual station, 1.5 for fixed automation, and 2.0 for a robot station.

Our analyses also assume that 2/3 of the investment is made in year zero and 1/3 in year one, and that savings may be accumulated over 11 years.

Finally, we follow current IRS rules in determining depreciation schedules and income tax rates.

The result of these assumptions is that we can generate a table of allowed investments or system budgets based on the assumed savings stream and a target rate of return, which in this case is 20%.
Results

Table 3 gives the results of this analysis for several candidate systems.

"Current manual" and "Baseline" are self-explanatory. "Serial, conveyor" is the name of a system that was designed entirely by our computer synthesis algorithm. The algorithm had complete freedom to choose people, robots, or fixed automation for each operation, and no assumptions were made about grouping operations at one station or making parallel stations. The computer made certain groupings to improve line balance.

"Parallel conveyor" is a system designed by hand and analyzed by computer. It assumes parallel station design and inverted monorails for material transport.

"Parallel AGV" is the same as the previous one except that AGV cost is substituted for monorail cost.

In both cases where AGV's are used, the taxi mode was assumed in order to determine transport cost. Even with this assumption, which is the most favorable one possible for AGV's, the systems with conveyors are more economical.

As noted in the introduction, these economic analysis results are sensitive to assumptions about task times. Several of these systems are close to saturation (including a 10% downtime assumption plus a third shift for maintenance), so small changes in task times may upset the capacity analysis and require the purchase of additional equipment. This, in turn, has obvious effects on the economics. Experiments would be necessary to make these estimates firmer.
Table 3. Comparison of Economic Study Results of Alternate Systems

Conclusions and Recommendations

Automation of axle assembly appears feasible. Without redesign, some operations must remain manual, and for some operations involving brake cables it is possible that no redesign will ever make them automatable. The recommended systems are mixes of people, fixed automation, and tool changing robots.

Automation is also economically attractive, based on a required 20% internal rate of return, and using cost estimates for robots, tools, fixed automation, transport systems, and engineering.

The client's baseline system assumed a 140-hour week using rolling 10-hour shifts. Both this operating scheme and one of 88 hours per week were analyzed, and systems were designed for both schedules. A major conclusion is that generally the 88 hour/week systems are the better investments, based solely on
the economics and leaving aside any personnel issues. The reason is that, due to difficulty of assembly and part provisioning, several operations are manual, requiring about 20 people assembling and 9 more kitting. The cost of shift and overtime differentials for these people during the 140 hour week outweighs equipment cost savings, making 88 hours/week better.

The baseline also assumed AGV's. We found that, on a cost basis, inverted monorail conveyors are clearly less expensive, even after including a complete ripout and rerouting (assuming AGV's, monorail vehicles, and most of the monorail track could be salvaged, and assuming that the monorails were placed on rather than below the floor).

Economic conclusions are based on cost and cycle time estimates. The conclusions are especially sensitive to the time estimates and these need to be verified by experiments. The conclusions are not as sensitive to the robot and tooling cost estimates.