

Spicer Off-Highway Products Division - Brugge

improves its Lead time and Scheduling Performance

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Spicer Off-Highway Products Division (a division of Dana Corporation) asked us to develop OR tools to improve the due date performance and to shorten the manufacturing lead time of its powershift transmission plant in Brugge, Belgium. We modelled the manufacturing system as a

queueing model, and used the model to analyze and evaluate improvement schemes (layout changes, product-mix decisions, lot-sizing decisions, and lead time estimations). Next, we developed a finite scheduler to improve the detailed scheduling of the shop. Our modelling effort contributed to the successful combination of analysis, planning and detailed scheduling. The plant increased productivity by 27.3 percentage points, decreased manufacturing lead times by a factor two to three, increased its workforce by 41 percent, and decreased its operating costs. The division is now profitable.

Dana corporation was founded in 1904 in Toledo, Ohio and now operates 330 production facilities and 38 research and development centers in 32 countries. It has 86,000 employees and its 1998 sales were \$ 12.5 billion. The corporation consists of seven major business groups: automotive components, engine components, heavy truck components, off-highway systems, industrial components, automotive aftermarket group and Dana commercial credit. The Spicer Off-Highway Products Division is part of the off-highway systems group. It serves the off-highway vehicles market including rough terrain-cranes, underground loaders, compactors, graders, excavators, dumpers, scrapers, specialty vehicles, and off-highway trucks. This group operates 15 plants. One of these plants is Spicer Off-Highway Products Division (SOHPD) located in Bruges (Belgium). SOHPD employed 680 people, and realized \$150 million in sales in 1998. They serve the OEM market with drive-train components such as transmissions, torque converters, axles and brakes. In producing transmissions and controllers, the division's core competence consists of the production of valves, clutches (shafts and gears), transmission cases, converter housings, controller hardware and software. The Bruges plant is Dana's worldwide R&D center for powershift transmissions.

The Business Case

Success in the business of supplying drive-train components for OEMs (Original Equipment Manufacturers) depends on technological competence and on the ability to deliver fast and on time; otherwise, niche producers will rapidly take over part of the business. Moreover, the high-technology product line faces product proliferation, and

consequently, we have to deal with small volume production in a highly uncertain assemble-to-order environment.

At the start of the project, in 1993, the total (average) manufacturing lead time was 16 weeks, whereas the customer lead time was on average 4 weeks. In other words, a lot of manufacturing operations are performed **before** it obtains the customer's commitment. The costs of mismatches are considerable. (excess stock and shortages, frequent rescheduling, inefficiencies in production, etc...) SOHPD produces some 460 different end products, 80 percent of these end items have an annual volume of less than 50 units (the mode is five). This of course results in an enormous variety of make parts, mostly produced in small volumes. Fifty percent of the parts have an annual volume of less than 100 units.

Back in 1993, our case company had a hard time to manage this complex environment. The plant layout was a typical job-shop arrangement and their MRP system (Manufacturing Resources Planning) could not deal with capacity problems and detailed scheduling. The poor operational performance eroded sales, and a negative spiral of events forced the managers to downsize (employment was reduced from 1,000 to 480 employees) and to start a series of reengineering projects. They asked the management science team of K.U.Leuven to develop a finite capacity scheduling system to remedy the scheduling problem. At that time, management recognized already the by now very well known flaws in MRP (ERP). The scheduling system in use was based on local, myopic priority sequencing rules.

The management science team and the management team soon found out that, although finite schedulers are powerful tools, the full leverage effect and the long term impact of the modelling effort could only be obtained by embedding the finite scheduling routine in a much broader context. We had to include OR tools to answer

questions such as: what are realistic lead time estimations, what are lead time minimizing lot-sizes, how does a change in layout (for example cell manufacturing) affect lead times, what is the impact of order acceptance, work release and due date assignment on the performance of the scheduling system, what safety time buffer do we have to use? All of these question are related to planning and analysis. We redesigned the project so that we could answer these questions.

A queueing network approach was suggested. We link queueing models and scheduling routines, we integrate OR tools for evaluation, planning and analysis with tools to perform detailed scheduling. A six year long fruitful cooperation between management scientists, managers and machine operators started.

The Original Planning System

The process of producing powershift transmissions is roughly a four-step process. First are rough machining operations on raw steel parts (forgings, bars). This takes place in the cold (soft) steel shop. Second, the steel parts are hardened through a heat-treatment. The third step consists again of machining operations but now on the hardened parts. This takes place in the hard-steel shop. The fourth step is a final assembly operation in which the rotating steel parts are built into housings. The housings are produced in the casting department. Our study deals with the planning of the rotating steel parts and more specifically the planning of the cold-steel shop.

Figure 1 illustrates the process.

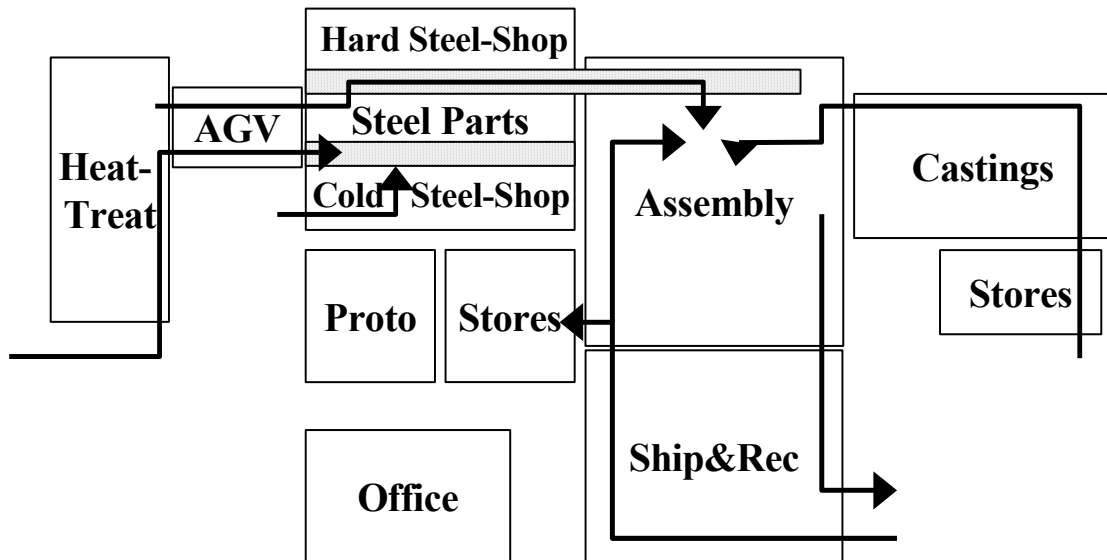


Figure 1: The four step production process of powershift transmissions: cold-steel shop, heat-treatment, hard-steel shop, and final assembly.

In figure 2 we give a detailed view of the cold and hard-steel shop.

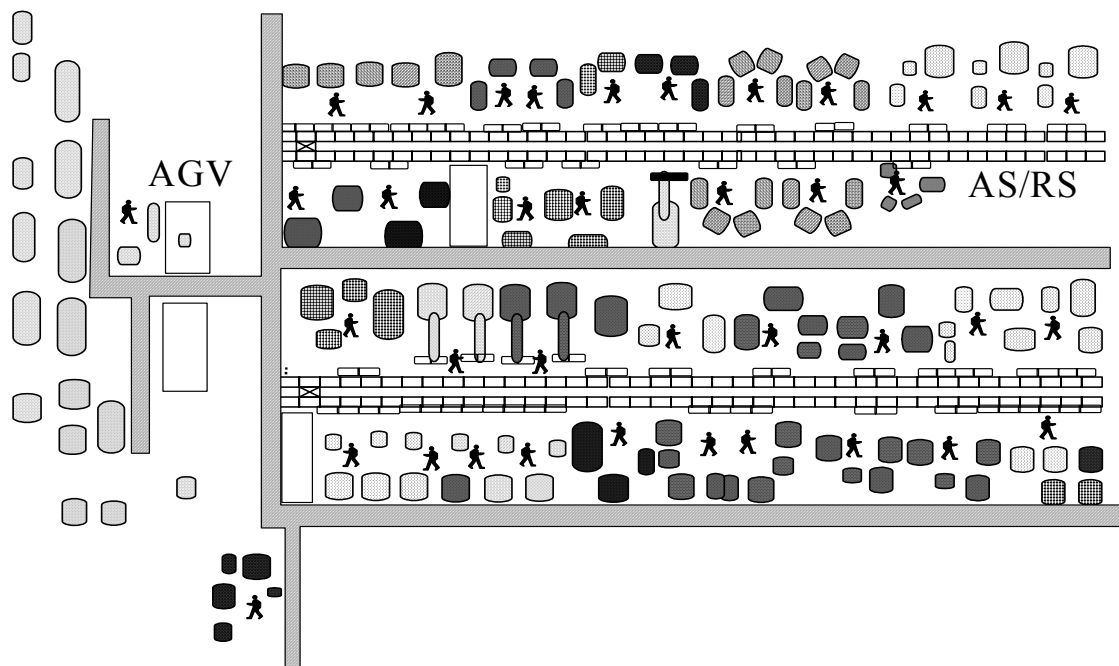


Figure 2: Detailed view of the hard (top part) and cold (lower part) -steel shop, the AGV (Automotive Guided Vehicle) and the AS/RS system (Automatic Storage and Retrieval System). All machines are arranged around two high-

stacker cranes. At the start of the project, machines were typically arranged in a job shop layout. Later on in the project management decided to adopt cellular manufacturing

Material handling is done by AGV's and an AS/RS system. The AGV system moves the parts from the cold-steel shop to heat-treatment and brings them back to the hard-steel shop. The AS/RS system stores all the steel parts' work-in-process. The pallets containing the steel parts move automatically to the input section of the machining center when that particular operation is activated or released. Machine operators make use of a 'queue' list (called the queue manager) and determine in a myopic way the sequence of the jobs to be done. They can activate the AS/RS system, parts are moved automatically to the machine and subsequently moved to a temporary stock location in the AS/RS system, from which they move again to another machine center until all operations are performed. The shop orders are generated by an MRP (Manufacturing Resource Planning) system, as will be discussed later on in this paper. The manufacturing lot-sizes are fixed at 1, 2, 4, 8, or 16 weeks of supply (power of two reorder intervals). Due to the large variety of parts, the high precision required and the small volumes, most of the steel shop was originally organized as a job shop, with a lot of general purpose machinery grouped in a functional way, in which products follow their own routings through the shop. The cold-steel shop has 70 machines, it fabricates 556 parts, requiring a total of 3,484 operations. The MRP system generates some 10,000 shop orders per year.

To conclude the description of the original planning approach, we have to mention the role of the MRP system. With respect to the final customer, SOHPD follows an

assemble-to-order strategy. It results in a final assembly schedule (FAS), and the material requirements routines translate the FAS into requirements for the hard-steel shop and the heat-treat department. The planned order releases of the heat-treat department in turn determines the production requirements for the cold-steel shop. The cold-steel shop and the heat-treat department typically operate in a make-to-stock environment. After heat-treat the plant switches to an assemble-to-order mode. In figure 3 we summarize the lead time structure.

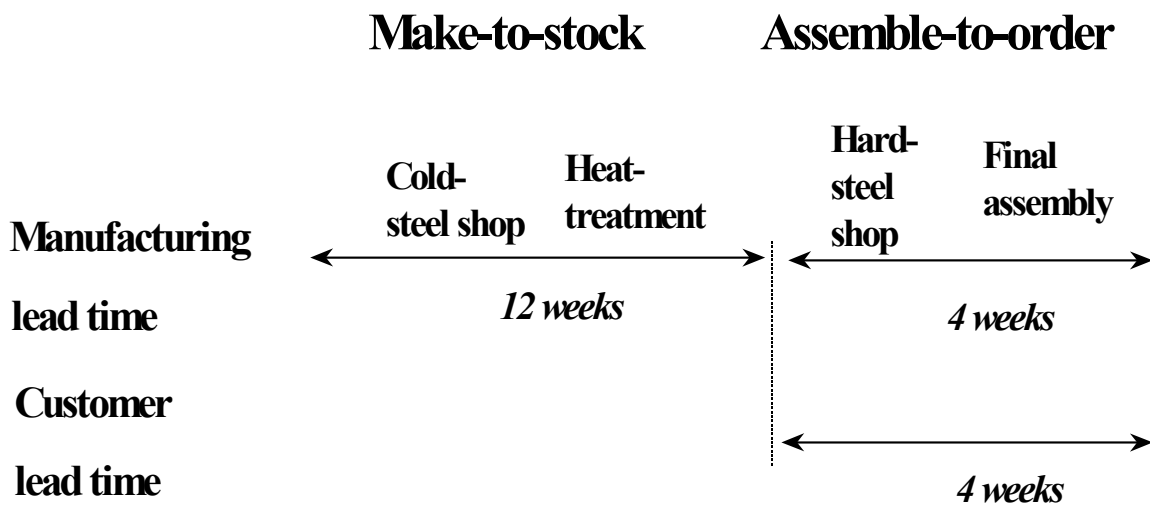


Figure 3: Lead Time Structure: SOHPD typically operates in a hybrid system of make-to-stock and assemble-to-order. Add to that the problem of high product variety and it is easy to understand that mismatches occur frequently. The costs of mismatches are considerable: excess stock and shortages, periods of idle time followed by overtime, frequent rescheduling, inefficiencies in production and missed due dates.

Planning and Scheduling the cold-steel shop are crucial. The problems encountered in this extremely complex cold-steel shop can be summarized by Thierry Tant, manufacturing manager (interview,1997):

“ The MRP system is a good calculator, but on the shop floor and on a minute-to-minute basis, we suffer from anomalies caused by rigid lot-sizing rules, predetermined lead times, the infinite loading practice, uncoordinated material and capacity plans, and a sequencing of jobs based on myopic priority dispatching rules (called the queue-manager). The availability of a dispatch list for each machine is a step forward, but it’s not enough. Every single planner we have in the plant is fully aware of what is called in every handbook the “garbage in, garbage out “ syndrome and, guess what; I am afraid this is exactly what we are experiencing.”

The diagnosis is clear. Installing a finite scheduling system alone won’t do the job. The real problems are rooted at a higher, more aggregated, decision level; such issues as lot sizing, the capacity structure, order acceptance and release policies are to be settled first. “We have to reconsider all of our procedures, all of our parameter settings, we have to change our shop-floor layout, we have to analyze the capacity structure, we have to involve our engineers to modify the design of our products and to improve the setup times and we have to convince the sales-order-entry people that they are key players in the whole process as well.”

All of this resulted in the development of ACLIPS: A Capacity and Lead Time Integrated Procedure for Scheduling [Lambrecht, Ivens, Vandaele,1998].

The New Planning and Scheduling System

ACLIPS is a hierarchical model in which we link a number of applications into an integrated planning and scheduling system. The management science team spent seven person-years developing and implementing the system. Implementation was gradual and was accompanied by a training program for the management team and the supervisors. We estimate that the training took a participation effort of 150 person-days. During the seminars, we focused on basic insight in operations management as described for example in Hopp and Spearman [1996]. We discussed the impact of variability and bottlenecks on response times. Stochasticity was a key concept in every discussion. We found this an extremely helpful way to involve many people and it made them less resistant to the OR specialists. During the whole project, we maintained a direct computer link between the plant and our offices, so that we could monitor the real-time impact of our decisions. The four phase hierarchical approach is summarized in figure 4.

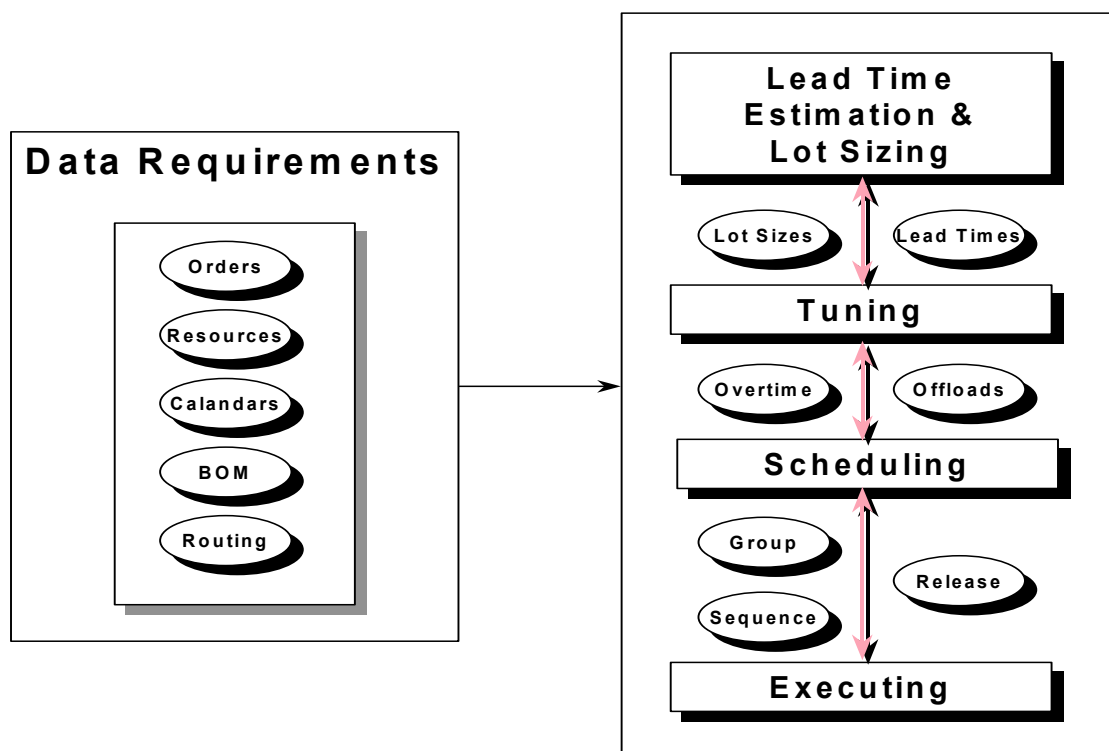


Figure 4: ACLIPS follows a four phase hierarchical approach combining short and long term considerations and stochastic and deterministic planning issues.

Phase one is the lead time estimation and lot sizing step. We modelled the cold-steel shop as an open queueing network. The job arrival patterns are derived from the MRP explosion process described above. Each order requires several operations, and the routing may differ from order to order. We explicitly include the stochastic nature of the production system, because of the many kinds of variability and disruptions. Note that we include setup times as well. This single class queueing network is formally exposed in the appendix. All the individual product streams are aggregated into an aggregate product stream. Adding up the aggregate expected machine lead times leads to the aggregate expected job shop lead time. This aggregate expected lead time can be considered as a weighted average of the individual expected lead times [Lambrecht, Ivens and Vandaele 1998]. We wrote mathematical expressions for the expected lead time and the variance of the lead time explicitly as a function of the lot-size. This is a convex function in terms of the individual product lot-sizes. This allows us to use an optimization routine to find the lead-time-minimizing lot-sizes for all parts simultaneously.

Second is the tuning phase. Management may consider the lead times as unacceptable and therefore decide to adjust the capacity structure (for example, permit overtime or otherwise expand), to off-load heavily loaded resources, or to consider alternative routings. All such adjustments require management intervention. The queueing model is an excellent tool to respond quickly to these requests. We found out that this capability of the model was one of the key success factors of the ACLIPS

implementation. The queueing model can be used to evaluate the impact of a cell layout on lead times. Indeed, management decided, later on in the project, to implement cellular manufacturing. Analysis of the product mix (unique product, repeat orders, large and small volume orders) is another interesting issue that can be tackled by the queueing model. The tuning phase is an essential intermediate stage before diving into finite scheduling. Phases one and two are typically executed once a month.

Third is the scheduling phase, which focuses on three decisions: (1) the grouping of requirements orders into manufacturing orders, (2) determining the release date for each manufacturing order and (3) the detailed sequencing of all operations. The queueing model (phase 1) produces target lot-sizes, which indicate how requirements have to be grouped into manufacturing orders. Recall that the requirements refer to the planned order releases of the heat-treat department. Given the time varying nature of these requirements, the manufacturing orders may actually differ from manufacturing order to manufacturing order, but on the average we aim for lot-sizes that minimize the expected lead times (and work-in-process).

The second decision is the determination of the release date of the manufacturing orders. The release date is set equal to the due date minus the lead time estimate of the manufacturing order. The estimate of the lead time is equal to the expected lead time plus a safety time. The safety lead time depends on the customer service. The lead time estimate is such that we expect to satisfy customer orders on time, at least 95% of the time. This of course requires knowledge of the variance and the probability distribution of the lead time. Each order is now characterized by a time window, it is hoped for that the estimates of the time windows are robust so that most of the due

dates are finally met, avoiding a constant need to re-plan. We do not treat lead time as a fixed and predetermined parameter; on the contrary, we constantly adjust the lead time to reflect the actual lead times. In this way, we avoid that the lead time estimate becomes a self-fulfilling prophecy.

The third decision concerns the sequencing policy. In the previous step a time window (expected lead time plus safety time) is created for every manufacturing order. Within these windows (one for every manufacturing order) we now have to sequence all operations in detail. We opted for the shifting bottleneck procedure [Adams, Balas and Zawack, 1988] for various reasons, one being its excellent performance as described by Ivens and Lambrecht [1996]. The shifting bottleneck procedure has to be adapted so that it can be used to sequence the operations for our general job shop environment including assembly operations, release dates, due dates, overlapping operations, multiple resources (machines and labor), setup times, calendars and many other real-life features. This sequencing application can clearly be interpreted as a deterministic real-time scheduler. It does not conflict with the previously described stochastic applications, on the contrary, the applications are complementary.

In the fourth and final phase, we transfer the detailed plans to the shop floor on a real-time basis. Through electronic data captation, information concerning the execution of the detailed plans is fed back so that rescheduling can be done. The nature and frequency of rescheduling heavily depends on the dynamics of the situation and the level of responsiveness required.

Methodological Issues

Our model builds on two well-known OR tools: queueing approximations and job shop scheduling algorithms. We had to modify both and add features to make them suitable for practical applications. [Vandaele 1996, Ivens 1997].

We adapted the queueing model along the following lines. We wrote expressions for the expected lead time and the variance of the lead time as functions of the lot-size. The model also explicitly includes setup times. Vandaele [1996] further extended existing approximations by including the following refinements: the average aggregate batch processing time, the squared coefficient of variation of the aggregate batch processing time, the selection of appropriate weights in the objective function, the determination of the squared coefficient of variation of the aggregated external arrival stream, a modified approximation for the variance of the lead time, the use of the lognormal distribution to approximate the lead time distribution function and the introduction of the concept of customer service. Simulations experiments [Lambrecht and Vandaele 1996] show that the approximations are accurate.

The scope of the theoretical job shop scheduling problem is too limited to be applicable in practical environments. Ivens [1997] extended the shifting bottleneck procedure so that non-standard features such as release dates, assembly structures, split structures, overlapping operations, setup times, transportation times, parallel machines, resource calendars and alternative performance criteria could be considered.

An efficiently written computer code is extremely important both in terms of internal memory requirements and execution time. We coded all mathematical procedures in C++ and designed a user-interface (Borland Delphi). SOHPD did a tremendous job in making accurate data available.

Benefits and Impact

The benefits and impact of our project are summarized in figure 5.

Quantitative	<ul style="list-style-type: none"> * 50%-60% Lead time Reduction * From 3.5 to 6 Inventory Turns * 27.3 Percentage Points Productivity Improvement 	<p>Economic impact:</p> <ul style="list-style-type: none"> * 41% Workforce Increase * 66% Sales Improvement
	<ul style="list-style-type: none"> * Development of Supporting Activities * OR/MS Awareness, Training Programs * Benchmark for new Implementations 	<ul style="list-style-type: none"> * Leveraged MRP/ERP * OR and Competitive Advantage
	SOHPD	Community at large

Figure 5: Both SOHPD and the community at large gained quantitative and qualitative benefits from our project

We first examine the quantitatively measureable improvements for both Spicer Off-Highway Products Division and the community at large. For SOHPD we improved lead times, inventory turns, and productivity. To verify the lead-time performance with ACLIPS, we conducted the following computer experiments. In the first planning experiment we evaluated the existing planning practice. The current planning practice involves the use of heuristically determined lot-sizes (fixed at 1, 2, 4, 8, or 16 weeks of supply) and the use of local, myopic priority rules for scheduling. In the second experiment we set the lot-sizes as obtained through the optimization routine and the scheduling is done by our extended shifting bottleneck procedure. The exact problem size concerned 556 different components, 70 machines, 3,484 operations and about 10,000 orders (cold-steel shop). To make things comparable, we used the ACLIPS model (the lead-time estimator and the finite scheduler) for both experiments but of course they had different parameter settings. The conclusion is that the average lead time (for the cold-steel shop) per order can be reduced by a factor three to four. We figured out that 85 percent of the lead time improvement is due to a better lot sizing policy and for 15 percent due to improved scheduling. [Lambrecht et al. 1998] The above mentioned lead time reduction is based on a computer experiment. Real-life data show that the lead time for final products decreased from the original 16 weeks on average, to lead times in the range of 6 to 8 weeks. A lead time reduction by a factor 2 to 3 is a realistic estimate. A secondary effect of this lead time reduction is a significant reduction of internal quality problems while yearly inventory turns have increased from 3.5 to 6. A

relentless search to reduce the total manufacturing lead time has led to a complete new layout of the plant, focused on cellular manufacturing. This was possible only after managers made a strategic decision, supported by Activity Based Costing information, to outsource all non-core processes and components.

SOHPD also uses a simple but effective productivity performance measure. The output of the company is translated into total numbers of standard hours produced (earned hours) and compared to the total direct hours (present hours). The ratio of standard hours produced over total direct hours is a measure of the direct productivity. This measure accounts for all kinds of outages. The standard times for the operations are regularly adjusted to reflect process improvement. The combined effect is what is called productivity improvement in Table 1.

	1993	1994	1995	1996	1997	1998
Direct Productivity	60.6%	65.5%	67.5%	67.8%	70.6%	72.6%
Standard Time Reduction	0.0%	2.9%	2.3%	2.8%	4.2%	3.1%
<i>Productivity Improvement</i>		7.8%	12.1%	15.2%	22.2%	27.3%

(percentage points)

Table 1: Direct productivity equals earned hours (standard processing time) over present hours. The standard times are regularly adjusted, consequently the sum of both measures fairly accurately describes productivity improvements.

SOHPD 's business succes has had a measurable impact for the community. The measurable impact for the community can be derived from the overall business success of SOHPD. The total number of employees increased by 41 percent over the

period 1993-1998. Over the same period, sales per full time equivalent improved by 66 percent.

The qualitative impact of our project is important. The ACLIPS model is only a relatively small component in the network of logistic activities that supports the business strategy. The use of the OR model induced several other supporting activities. Let's illustrate this point with a simple example. The data required to run the shifting bottleneck procedure are such that several specific tools had to be developed by the systems department to obtain the data in a structured and systematic way. Each machine operation for example is now identified by its 5 most important setup characteristics ranked in order of changeover time required. This allows us to implement a sequence dependent setup time routine to minimize the setup time loss. Indices to measure product variety were developed as well. SOHPD also developed a monitoring system to manage the projected availability of raw materials against the planned release dates of manufacturing orders. It thereby coordinates its capacity and material plans.

The ACLIPS project has fostered a general awareness for scheduling and planning issues throughout the whole organization. Operations management issues are on the agenda for management training and also for the training of the shop floor workers. As a matter of fact, a four hour intensive training session on production planning and scheduling has become an integral part of the training program for all employees. A final qualitative benefit for SOHPD is the fact that the production planning and control system of the plant in Bruges is used as a benchmark for the implementation of a new Y2K compliant planning system for the plant in Statesville, NC.

Finally we believe there are also important benefits for the community. First the insights obtained from the ACLIPS approach are applicable to a wide range of

manufacturing companies. It remedies some basic flaws in MRP/ERP. Second, we have a more general reflection that puts our work in an industrial policy context. European manufacturers operate under severe cost pressures. The high cost of labor and restrictive practices are often cited as major competitive disadvantages resulting in the delocalization of manufacturing activities. The SOHPD case shows that a focus on optimization accompanied by supporting, complementary activities can easily outweigh these disadvantages. Our project shows that a coherent bundle of OR tools creates a competitive advantage.

APPENDIX: SOHPD Problem Formulation and Solution

A complete description of the OR models we used would be elaborate and extensive. To give an idea of the decision logic, the major methodological issues and the solution techniques are summarized below. We simplified notation drastically. We use the following notation:

- i the product index, $1, \dots, N$
- j the machine index, $1, \dots, M$
- l the operations index, $1, \dots, O_i$
- δ_{ij} equals 1 if operation l for product i is on machine j , zero otherwise
- Q a vector of lot-sizes, decision variable, a multiple of the average customer order quantity OQ
- Y the interarrival-time random variable

- T the setup-time random variable
- X the processing-time random variable
- OQ the customer-order quantity
- MO the manufacturing-order quantity
- W the lead-time random variable
- E(.) the expected value of a random variable
- V(.) the variance of a random variable

The decision problem can be formulated as follows:

(1.) Obtain for each product the optimal production quantity minimizing the average product lead times.

The overall objective function is

$$f(Q) = E(W) = \sum_{j=1}^M E(W_{q_j}) + \sum_{j=1}^M \sum_{l=1}^N \sum_{i=1}^{O_i} \pi'_{jl} (\bar{T}_{il} + Q_i \overline{OQ}_i \bar{X}_{il}) + \sum_{i=1}^N \pi'_i \frac{(Q_i \overline{OQ}_i - 1) \bar{Y}_i}{2 \overline{OQ}_i}$$

and stands for the aggregate average lead time for a product through the entire shop. The first term sums the waiting times over all machines (using a general two moment approximation), the second term sums the aggregate weighted (π'_{jl} = the weight of operation l on machine j) average batch processing times of all machines and the third term sums the weighted (π'_i = the weight of product i on the shop) average time in the final inventory. This is a N-dimensional, non-linear function subject to traffic intensity constraints, queueing network constraints (scv's of internal interarrival times) and constraints to prevent batch splitting. Based on extensive numerical

experiments, we conjecture that the function is unimodal. We use a dedicated numerical approximation gradient technique to find the overall minimum. The determination of a good feasible starting solution is crucial for the algorithm. This starting solution is obtained from the multiproduct economic lot-size scheduling problem literature (ELSP).

(2) Group the actual requirements optimally into manufacturing orders

Given the optimal lot-sizes for each product $Q_i^* \overline{OQ}_i$, an equivalent optimal number of setups can be derived for a particular planning period. We use an efficient dynamic program to allocate individual product requirements to the optimal number of manufacturing orders. The average batch size of manufacturing orders (\overline{MO}) approaches asymptotically the optimal lot-sizes obtained in (1).

(3) Given the due date of manufacturing order p for product i (MO_{ip}), perform a lead time offset and obtain a release date

First obtain the expected lead time for each manufacturing:

$$E[W(MO_{ip})] = \sum_{l=1}^{O_i} \sum_{j=1}^M E[W_{q_j}(Q_i^*) \delta_{ilj}] + \sum_{l=1}^{O_i} (\overline{T}_{il} + MO_{ip} \overline{X}_{il})$$

In addition obtain an expression for the variance of the lead time:

$$V[W(MO_{ip})] = \sum_{l=1}^{O_i} \sum_{j=1}^M V[W_{q_j}(Q_i^*) \delta_{ilj}] + \sum_{l=1}^{O_i} [V(T_{il}) + MO_{ip} V(X_{il})]$$

The first term in the above expression for the variance is a general two moment approximation. If we postulate a lognormal lead time distribution $F(W)$ with parameters μ and σ^2 , we obtain (through the standard transformation for the lognormal):

$$\mu = \ln \left(\frac{E[W(MO_{ip})]}{\sqrt{\frac{V[W(MO_{ip})]}{(E[W(MO_{ip})])^2 + 1}}}} \right)$$

$$\sigma^2 = \ln \left(\frac{V[W(MO_{ip})]}{(E[W(MO_{ip})])^2 + 1} \right)$$

Given this full characterization of the lead time W , we can obtain any lead time percentile, which will be used for lead time offsetting. It guarantees a specified level of customer service for each product. Vandaele [1996] gives further details.

(4) A scheduling routine sequences the operations between the release date and the due date

The scheduling routine we used is an extended version of the shifting bottleneck procedure. It schedules all operations in time windows determined by the release and due dates satisfying all precedence relations and resource constraints. In addition, we included a number of realistic extensions.

Acknowledgments

This research is supported by the Science Foundation of Flanders (FWO-project G.0063.98), the BOF fund of UFSIA and the Tractebel Chair.

We are grateful for all support we received from the personnel at Spicer Off-Highway Products Division, Dana Corporation.

We dedicate this work to our friend Philip Ivens who passed away on April 17, 1998. Philip was in the final stage of his Ph. D. work, he designed and implemented the scheduling system, the database architecture and the graphical user-interface. This project would never have succeeded without his dedication and hard work.

References

Adams, J., Balas E., and Zawack D., 1988, "The shifting bottleneck procedure for job shop scheduling", *Management Science*, Vol. 34, pp. 391-401

Hopp, W., and Spearman M.L., 1996, "*Factory Physics, Foundations of Manufacturing Management*", Richard D. Irwin, Homewood, Illinois

Ivens, P. and Lambrecht M.R., 1996, "Extending the shifting bottleneck procedure to real-life applications", *European Journal of Operational Research*, Vol. 90, pp. 252-268

Ivens, P., 1997, *An integrated shifting bottleneck procedure for scheduling*, Ph. D. thesis draft, Department of Applied Economics, Katholieke Universiteit Leuven, Belgium

Lambrecht, M. R., Ivens P., and Vandaele N.J., 1998, "ACLIPS: A Capacity and Lead time Integrated Procedure for Scheduling", *Management Science*, Vol. 44, pp. 1548-1561

Lambrecht, M. R., Chen Shaoxiang, and Vandaele N.J., 1996, "A lot sizing model with queueing delays: the issue of safety time", *European Journal of Operations Research*, Vol. 89, pp. 269-276

Lambrecht, M. R., and Vandaele N.J., 1996, "A general approximation for the single product lot sizing model with queueing delays", *European Journal of Operations Research*, Vol. 95, pp. 73-88

Vandaele, N. J., 1996, *The impact of lot sizing on queueing delays: Multi product, multi machine models*, Ph. D. thesis, Department of Applied Economics, Katholieke Universiteit Leuven, Belgium