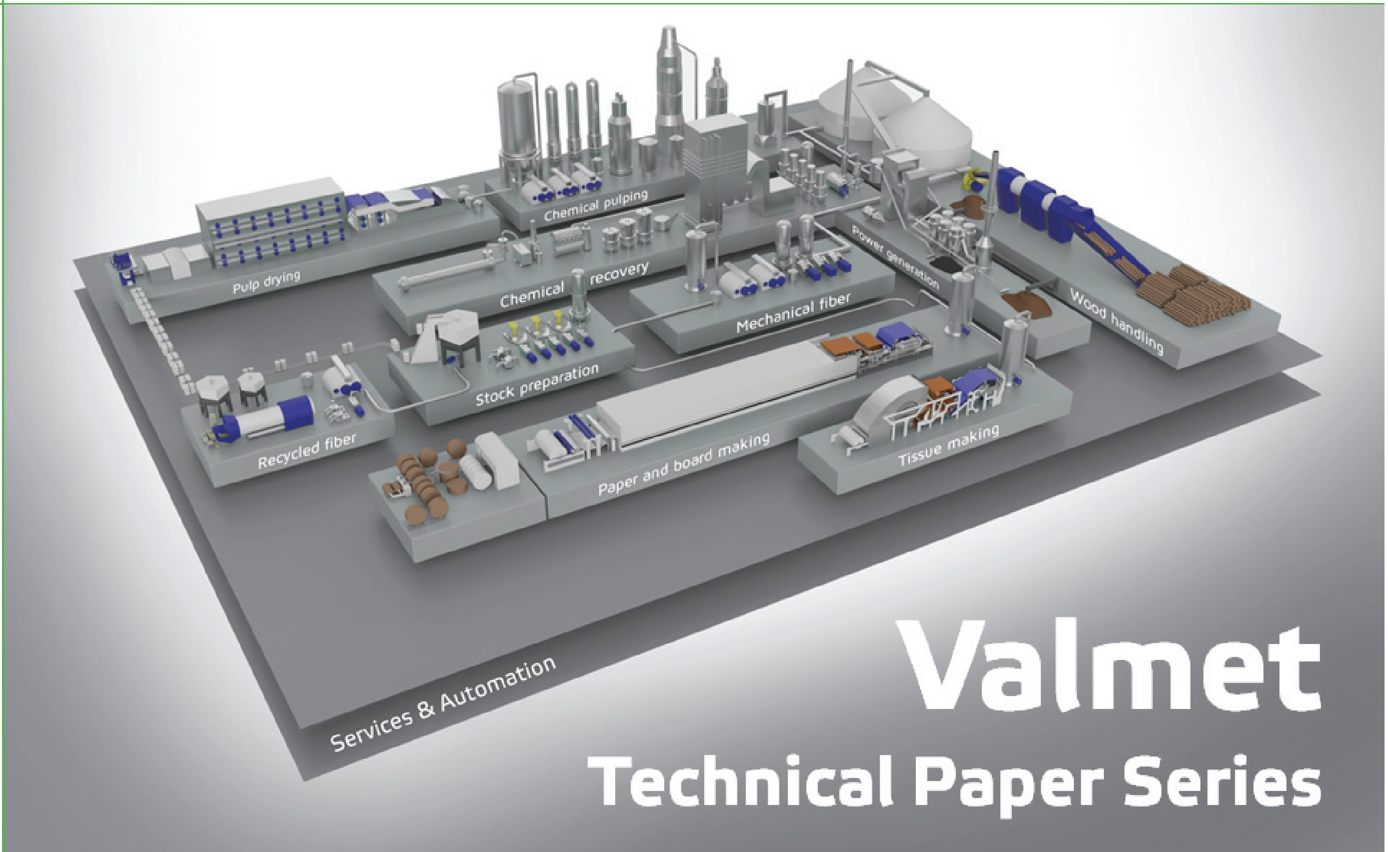


Digital hydraulics

Executive Summary

The concept of digital hydraulics has been around for quite a while, but is only recently that digital hydraulics in the pulp and paper industry have been commercially feasible. By using digital hydraulics, fragile and expensive proportional valves are replaced with multiple inexpensive and robust on/off valves. The results include higher reliability, lower energy usage, more accuracy in machine movements, fewer shutdowns, less lost production and lower initial investment and spare parts carrying cost.

Digital hydraulics replaces standard proportional valve applications with parallel groups of simple, quick-acting, binary on-off valves. Since the poppet style valves do not leak, there is no need to have a pump running all the time. This significantly decreases energy consumption. Instead of using a large hydraulic power unit (HPU) - a small HPU and an accumulator are provided, located on the machine floor requiring no piping run up from the basement.

"Digi-valves" are mass produced, robust, small and inexpensive compared to proportional valves, which contribute to a lower initial investment and carrying cost for spares. If one digi-valve fails, operation automatically reconfigures the remaining valves for very little impact on performance. Compare this to a proportional valve failure which brings the process to a halt and can damage roll covers.

This white paper presents both the technology and case study results.

Digital vs. analog hydraulic control - the basics

Hydraulic control valves are a fundamental part of pulp, paper, board and tissue machinery. They allow fluid flow into different paths from one or more sources, and typically consist of a spool inside a cylinder which is mechanically or electrically controlled. The movement of the spool restricts or permits the flow, thereby controlling the fluid flow. This is necessary when moving large heavy equipment accurately and safely.

The proportional valve (**Figure 1, left**), a type of directional control valve, requires a continuously running pump to combat leakage and flow losses. The valves are expensive and relatively fragile, and require auxiliary devices to function correctly (counterbalance, anti-cavitation, etc.). Each type of proportional valve is designed for specific conditions, so there are a huge number of valve variations. There is no fault tolerance; when the valve goes, it's gone.

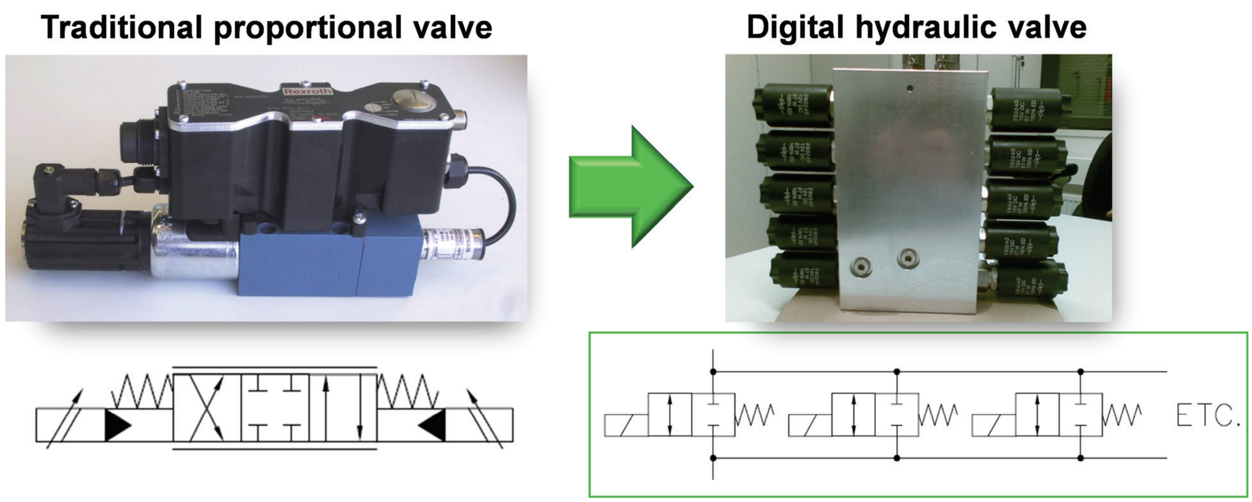


Figure 1. Conventional analog proportional valve and circuit (left) compared to digital hydraulic valve and circuit (right).

With digital hydraulics (**Figure 1, right**), a combination of simple, robust and inexpensive on/off valves serve the same purpose as a single proportional valve. The PLC automatically takes care of turning the valves on and off in order to provide highly accurate flow and pressure, for a less expensive cost than using a proportional valve.

Valmet has been involved in bringing digital hydraulics into practical use in the pulp and paper industry for several years, working with universities and government consortiums. Although the basic principles have been known for quite a while, digital hydraulics were not commercially feasible in the pulp and paper industry due to lack of suitable control system, fast I/O devices and algorithms.

It requires vision to be the first to recognize upcoming technologies which have true potential. Taking full advantage of these new technologies requires the ability to look at traditional designs from a new perspective and redesign them as needed. Using Valmet's vision, digital hydraulics technology is now ready for industrial use and has proven itself in several installations with significant benefits (**Figure 2, next page**). There are now several digital hydraulic and pneumatic reference machines including calenders, doctors, winders, reel and press section using patented Valmet applications.

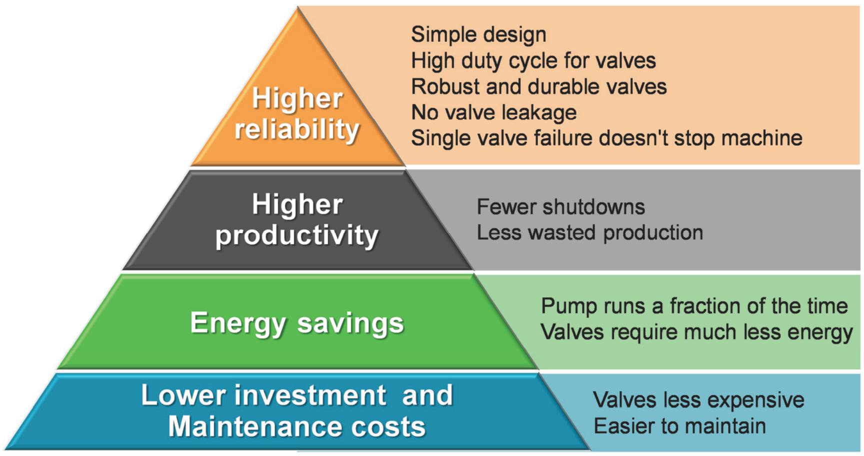


Figure 2. Proven benefits of digital hydraulics compared to conventional hydraulics

According to the development manager at Valmet, who leads Valmet's pulp and paper industry digital hydraulics application development, it has been a long uphill climb, but worthwhile: "The digital hydraulics development project provided Valmet with leading digital hydraulic developer contacts. In the beginning there was no acceptable technology in existence. Significant development has been carried out with control system hardware, software and hydraulics. Delivering a digital hydraulic system to a paper machine involved Valmet defining the requirements for each section. With these requirements achieved, several customer projects in mills have since been delivered."

The remainder of this paper discusses the technology and case study results…

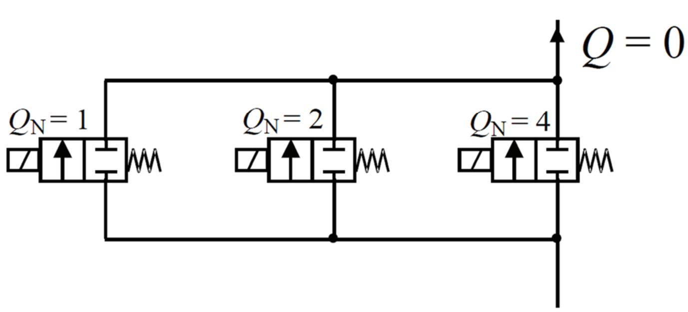
Background

Digital hydraulic development at Valmet began at the Järvenpää facility in 2007. The first pilot machine application was built and tested. At that time there were no components dedicated to digital hydraulics. While the pilot machine automation was not suitable for a paper mill, the functionality of the system could be tested and was found to work perfectly.

The feed forward Simulink-based calculations created and used on the pilot machine have been used ever since. They have been modified to work with different sections of paper machine lines.

The poppet valve is a normally closed 2-way valve which blocks inlet flow when in the unactuated position, and passes inlet flow when actuated. The valves are mass produced, durable, and much less expensive than proportional valves. Binary programming is used in a PLC to control the valves. Ideally, the valves must be very fast, on the order of a few milliseconds to change state between open and closed.

A simple example of digital hydraulics is shown in **Figure 3**, where there are three valves each with a different flow capacity. By selectively



V1	V2	V3	Q
0	0	0	0
1	0	0	1
0	1	0	2
1	1	0	3
0	0	1	4
1	0	1	5
0	1	1	6
1	1	1	7

Figure 3. Digital Flow Control Unit (DFCU) and binary state table

turning the valves on and off, the individual valve flows are combined to form a total flow using a binary table. The valves would typically have flow rates of 1, 2, 4, 8, 16, etc. according to the binary system. The example shows a three-valve system with individual valve flow rates of 1, 2 and 4. When treated as a single unit (in this case we call it a digital flow control unit, or DFCU), the flow ranges from 0 to 7 in one unit steps.

If more precise flow rates are required, more valves may be used. For example, a proportional valve might use 4 valves, giving a flow rate from 0 to 15. A servo valve might use 6 valves, for a flow rate from 0 to 63. A comparison between a proportional valve response and a 4-valve DFCU and 6-valve DFCU is illustrated in **Figure 4**.

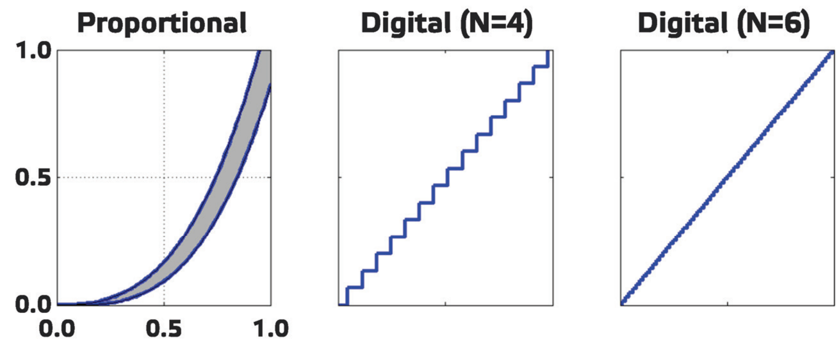


Figure 4. More valves provide a smoother response curve (N = # of digi-valves).

The functionality and characteristics of the digital hydraulics system are defined by the software, rather than additional hydro-mechanical components. The software is adaptable for different loads and actuators. The resulting valves are multi-purpose, i.e. for controlling position, force, pressure, speed, etc. Variations in line pressure and/or temperature are automatically compensated for.

Benefits of digital hydraulics

There are several benefits to using digital hydraulics as opposed to proportional valves. The first and most important is reliability.

Reliability

Traditional proportional valves contain many delicate components such as microprocessor, digital signal processor and A/D + D/A converters. The valves are located out in the field, where they are exposed to high temperatures and vibrations shortening their life expectancy considerably. The inevitable failure of a proportional control valve in the best case will only stop the process, bringing the calender down until the valve is replaced. In the worst case, the roll cover - an expensive consumable - is damaged and must be replaced, requiring significant down time.

Proportional valves also leak - by design. The spool of the proportional valve must move in both directions, which is why there is no sealing face (unlike digi-valves which have a sealing face). Instead there are tight manufacturing tolerances between the spool and the housing. The high pressure levels needed in the hydraulic circuits generate an oil flow past the spool which cannot be avoided. A typical flow rate is 0.40 – 0.65 l/min for proportional valves.

By comparison, the poppet valves used in digital hydraulics are simple and robust. They are insensitive to contamination, and up to 30 times more tolerant of oil impurities. They also tolerate much higher oil temperatures, 300 °C vs. 75 °C for analog valves; thus there is no need to cool the hydraulic power unit. There is also no need for spool position feedback. Zero-leak poppet valves exist, and low-cost mass production of them is possible. The control electronics are simple. A poppet valve is good for 300 million to 1 billion work cycles. Thus no unscheduled shutdowns or reduced quality occur due to the digi-valves.

Rather than use a hydraulic unit, an accumulator is provided by Valmet in loading cylinder controls to accompany the small hydraulic unit. There is a predicted significant 90%-plus improvement in cycle efficiency for pressure accumulators, making hydraulic energy recovery and re-use a highly attractive solution that dispenses with the need to transform energy between hydraulic and electric forms. NOTE: Some projects use an existing hydraulic unit, in which case the accumulator is not needed.

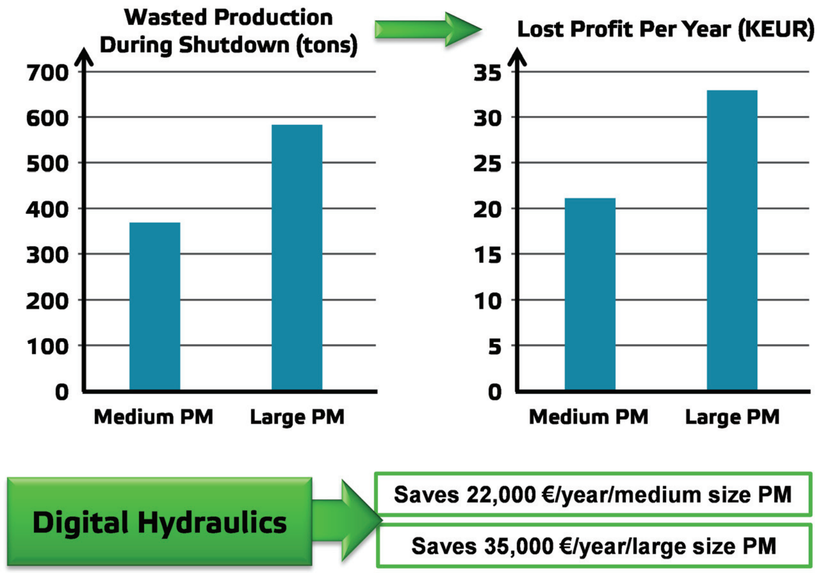


Figure 5. Depending on paper machine size, the reliability of digital hydraulics reduces lost profit by up to 35,000 EUR/year.

Figure 5 shows examples of the value of higher reliability with digital hydraulics in a medium and large paper machine. The medium machine runs at 1200 m/min with a web width of 7.8 m. The large machine is 10.2 m wide and runs at 1450 m/min. Both produce 110 g/m^2 sheets, with a sale price of 300 EUR/ton. Both run at 95% machine utilization, with one shutdown/year lasting 6 hours. Lost profit is calculated at 20% of the value of lost production. The savings range from 22,000 to 35,000 EUR/year.

Energy reduction

The programmability of digital hydraulics can minimize energy consumption. The most cost-efficient "spool" is used at any time. Only a few of the digi-valves are open at the same time. Actually there can be times in a nip control application when none of the valves are open for quite some time. In a steady state load situation the valves can be closed once the requested pressure level inside the cylinder has been reached. Since the poppet valves do not have an unwanted oil flow past the spool (i.e. zero leakage), the pressure level remains steady for longer times and the valves do not have to be reopened.

This results in 36% smaller energy losses than in a traditional load sensing system, as seen in **Figure 6**.

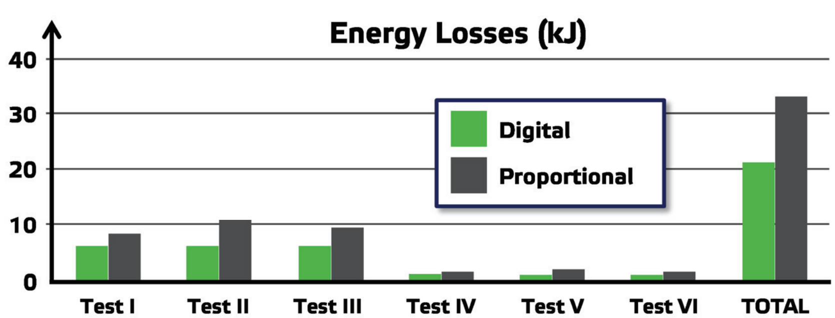


Figure 6. Digital hydraulics reduces energy consumption in a load sensing system, as compared to analog hydraulics.

Another energy reduction example is seen in **Figure 7**. This was a ValHard on-machine calender rebuilt from conventional analog to digital hydraulics. The conversion resulted in a savings of 12,800 EUR/year.

On a machine calender over 28 days, an amazing 98.6% reduction in energy use was recorded (**Table 1**). This was almost entirely due to the pump not needing to run continually. With digital hydraulics, the pump was only used for a total of one minute to increase the pressure in the system.

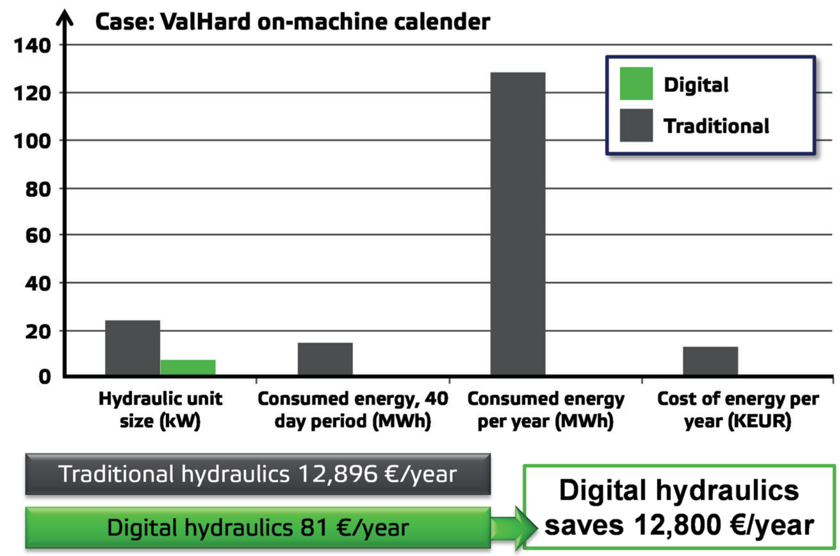


Figure 7. Digital hydraulics reduces energy cost on a ValHard calender by > 98%.

	Traditional	Digital	Savings
Pump	4435.2 kWh	0.3 kWh*	**99.993 %**
Valves	64.5 kWh	64.2 kWh	**0.5 %**
TOTAL	4499.7 kWh	64.5 kWh	**98.6 %**

** 0.3 kWh corresponds to ~1 minute of pump operation.*

Table 1. Digital hydraulics energy use was dramatically lower than traditional hydraulics over a 4-week 24/7 run on the calender.

Lower cost of spares

Only a few types of valves are needed, for example a 64 l/min, an 8 l/min and a 1 l/min valve. These would then be combined to make any "virtual" valve needed. In practice, only four different two-way on/off valves are sufficient.

Repeatability, response and productivity

Digital hydraulics offers perfect repeatability. The individual valves are either completely open or completely closed. There is no need for spool position feedback.

Digital hydraulic control utilizes a model-based control technology and an efficient high-speed algorithm to make control both faster and more accurate than that achievable with conventional analog hydraulics. The poppet valves are faster and they have a linear behavior without hysteresis. The pressure levels and the amount of oil flowing in and out of the cylinder are known accurately. The metering edges (P-A, P-B, A-T, B-T) are controlled independently, enabling full control over flow rates and pressure levels. This is why the digital hydraulic control is superior to traditional technology.

No switching is needed to maintain any discrete opening value. Thus there are over 99% fewer switchings that take place. The switching time is also 100 times faster response than with traditional pulse width modulation (PWM) control. Using two position on/off poppet valves it is easy to optimize for response time. Also, the response time of a multi-valve DFCU is independent of the amplitude, due to the parallel connection. The faster response and faster closing/opening of the nip, combined with no overshooting in transition situations (**Figure 8**) result in more saleable production and therefore higher productivity.

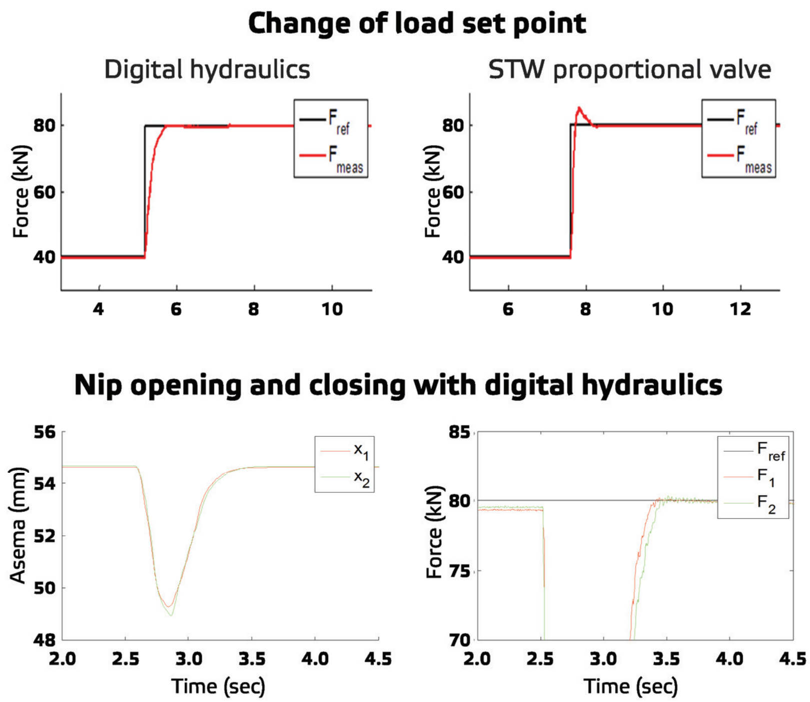


Figure 8. The response of digi-valves in a digital hydraulics system is superior to that of conventional analog hydraulics.

An off-machine calender was rebuilt to replace conventional with digital controls, and the productivity results were measured and compared in **Figure 9**. The calender speed was 1000 m/min, with a web width of 10.2 m and it ran a sheet with basis weight of 45 g/m^2. The sale price of the paper was 500 EUR/ton. Machine utilization was 95%. There were 24 nip closings/day. The savings with digital hydraulics approached a half million euros/year!

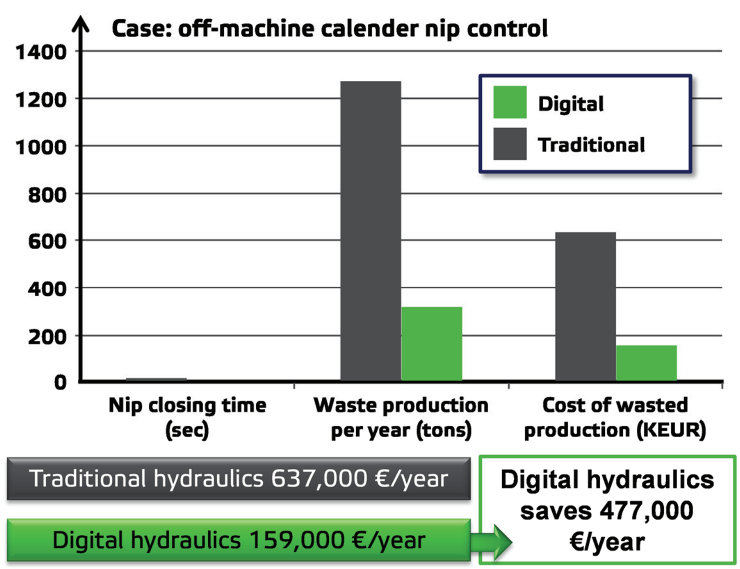


Figure 9. Digital hydraulics saves almost a half million euros in lost production per year, compared to traditional analog hydraulics.

Fault tolerance and scalability

Fault tolerance is one of the greatest benefits of the digital hydraulics system. If one or more valves fail, the software will reconfigure the valve combinations to provide a relatively smooth response. **Figure 10 (next page)** shows the change in discrete output values from an original system, to a system with a valve failure - before and after the software has reconfigured output values. Diagnosing faults of digital valve systems is also much easier than for analog valves.

Even open valves can be compensated for. The system automatically compensates by opening a "counter valve." For example if a valve in the P-A metering edge remains permanently open, a similarly sized (counter) valve in the A-T metering edge is opened. This will increase unnecessary oil flow, but the system is able to operate until the next scheduled shutdown.

If there is a sudden peak load, such as when a wad of paper goes through the nip, the digital hydraulics will compensate much faster than a traditional system. In both digital and conventional systems, however, the use of pressure relief valves which are set to open when a safe pressure level is exceeded is advised.

A digital hydraulics system is highly scalable. This means that adding just one additional valve will either double the flow rate or double the resolution. These characteristics improve exponentially as the number of valves increases.

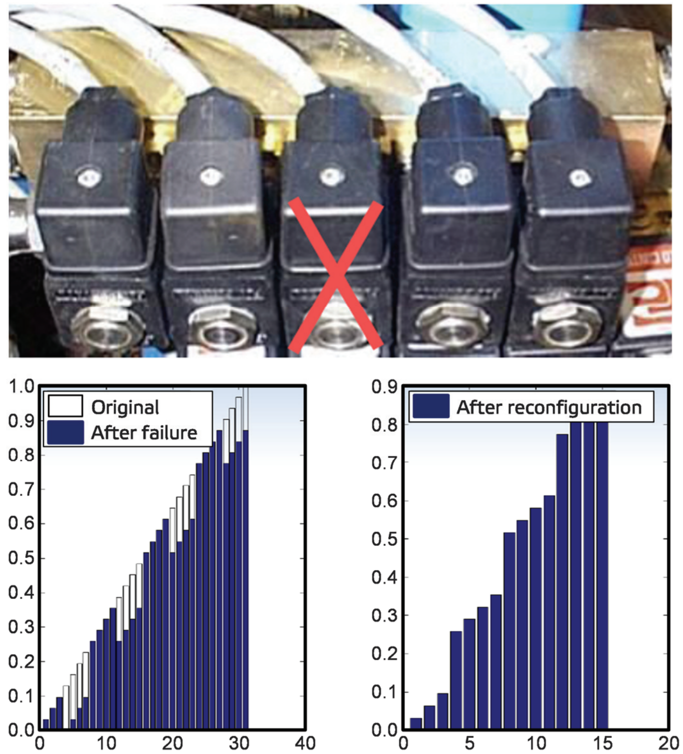


Figure 10. If one digi-valve fails, the remaining valves are automatically reconfigured to produce a response curve that allows the machine to continue to run.

Rebuilds

Digital hydraulics are not just found in new equipment deliveries by Valmet, but also in several rebuilds. Existing hydraulic units can be used, as well as existing hydraulic cabinets, with no changes in piping. Alternatively, a small HPU may be installed with minimal field piping required (**Figure 11**).

In the case of controlling nip pressure, up to 98% savings in energy can occur. By using digital hydraulics to control the supply pressure of SymCD rolls, the energy savings will range from 25 to 60% depending on the level of nip load.

Figure 11. Using a smaller HPU and an accumulator reduces equipment and field piping costs.

Digital pneumatic control

In a similar manner, pneumatic analog controls may be replaced with their digital equivalents. Valmet has rebuilt swimming roll deflection, doctor blade and sizer nip control systems with digital pneumatics. Diagnostics are improved because hose leakages are easily determined, as well as the rough amount of leakage. With no valve leakage, and the correct loading pressure always used, there are savings in pneumatic energy. There is highly accurate pressure control with pressure feedback. Only one type of valve is needed, as there is not much flow in doctor and swimming roll actuator applications. This minimizes hardware and spares, plus there is no need for high precision pressure reducers or proportional pressure control valves.

CASE STUDY - Multinip calendering

Hydraulics play a major role in the calendering and sizing process (**Figure 12**). The tend side and drive side cylinder movements must always be synchronized. Exceeding the loading pressures is not allowed while the nip is closing. The position and pressure reference values must be followed very accurately, in order to create a good paper thickness profile.

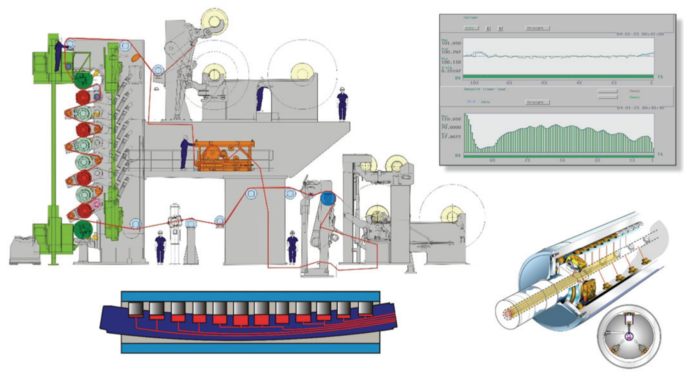


Figure 12. A multinip calender requires precise hydraulic control at high pressures for loading and relieving as well as precise and robust control of loading shoe pressures.

In a multinip calender, there are more than two rolls in the stack. The purpose of the calender is to increase gloss and smoothness by using high loads and temperature. Profile and loading levels are controlled with loading cylinders, relieving cylinders and CD roll internal pressures. The pressure setpoints are calculated with model-based MATLAB calculations.

In the spring of 2012 the first multinip calender with digital hydraulics was sold by Valmet. The customer previously had many problems with proportional valves. Using digital hydraulics was a major reason Valmet was awarded the project.

The multinip calender (**Figure 13**) included:

- two stacks with four CD rolls
- 26 hydraulic loading zones per roll
- a total of 104 control points in the rolls
- 4 loading cylinders
- 4 relieving cylinders
- lubrication control for the CD rolls
- digital pneumatics for doctor controls
- ~1500 digi-valves

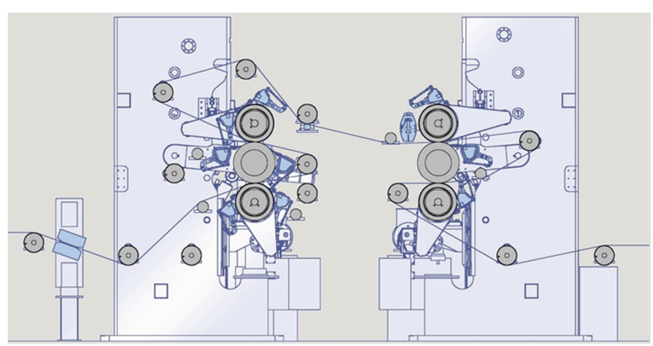


Figure 13. The first multinip calender with digital hydraulics was installed in 2013.

A lot of new technology development was needed for the project. This included CD roll hydraulics and controls, booster electronics, lubrication controls and a web server for the digital hydraulics.

CD roll hydraulics and controls

The CD roll shoe is controlled by pressure, but there is a continuous oil flow. More digi-valves were needed as compared to non-leaking pressure control. Eight binary coded valves were used for one shoe loading (**Figure 14, bottom**). The valve orifice calibration was modified to check all states of the DFCU.

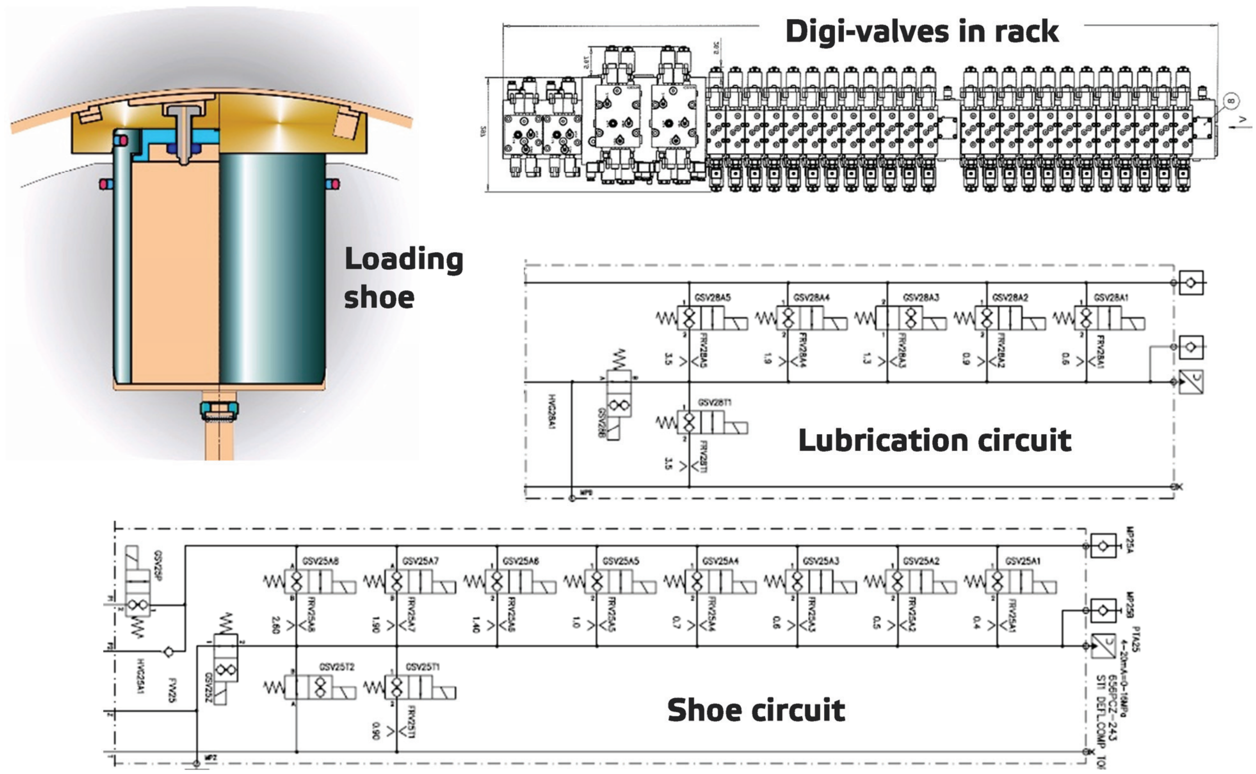


Figure 14. Digital hydraulics controlled loading and relieving, as well as the individual loading shoes and lubrication.

A load sensing function was developed in order to save energy. The possibility to select high or low supply pressure for a shoe was added. After one year of running 25 – 30 % energy was saved.

CD roll lubrication oil flow was controlled for the first time with digital hydraulics in this installation (**Figure 14, middle right**).

Valves and boosters

Valves at that time were too big and too slow. So Valmet started cooperation with hydraulic valve manufacturers to develop suitable components.

Finally a smaller valve was available. The valve was an old model, but the coil was modified to make it fast enough, less than four milliseconds. The resulting valve was actually smaller than the older valve, which helped save space (**Figure 15, left, next page**).

The valves opened and closed too slowly with 12 VDC voltage, therefore boosters were needed to increase the open/close pulse to 48 VDC and the coil was designed to need a booster circuit to move the spindle. There were no commercial boosters available. Valmet had already developed a DIN-rail mounted booster, but with about 100 units it took too much space. So Valmet designed a new version to be compatible with

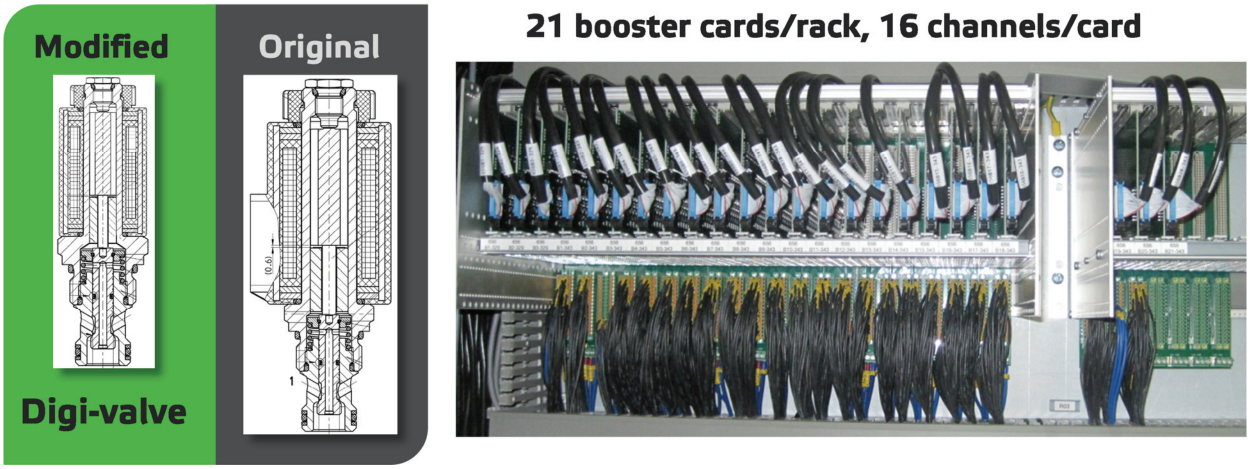


Figure 15. Valmet worked with a valve manufacturer to reduce the size and speed up poppet valves, and designed a space-saving booster card.

a commercial 16-channel binary output card. The same electronics were modified to fit in a 19 inch rack (**Figure 15, right**).

Electrification

Wiring of 1500 valves with standard methods was too difficult, so special cables were ordered. The 12 VDC power supplies for the valves were able to deliver totally over 1200 A.

Control system and software

Valmet made a cooperation agreement with Beckhoff to be a beta tester of their new Twincat3 control software. With this new system it was possible to program with Simulink; all the communication and I/O of the PLC was available.

The digital hydraulic control system itself does not need any internal adjustment by maintenance. The process can be adjusted normally. This is similar to automobiles where the use of digital control systems has resulted in more reliable cold starting behavior, lower fuel consumption and lower emissions. Yet the car's driver does not need to continually adjust the fuel and ignition equipment. The same holds true for digital hydraulics.

Additionally it was found that there were too many parameters to track, so web server displays were developed. An additional benefit of this server is that the displays can be opened somewhere else in order to monitor the digital hydraulics performances, such as via remote support.

New functions to the multi-nip calender Simulink software were developed, including:

- Calibration of CD Roll orifices
- Diagnostics
- Stack quick open
- Load sensing
- Web server, remote control and Simulink parameters
- Lubrication control

Excellent results

Startup of the multi-nip calender was successful, and the customer has been satisfied with the delivery. Only small fine-tuning was needed after startup. Complicated functions were easy and fast to create with Simulink programming. However, not all savings were achieved because some of the traditional system was maintained.

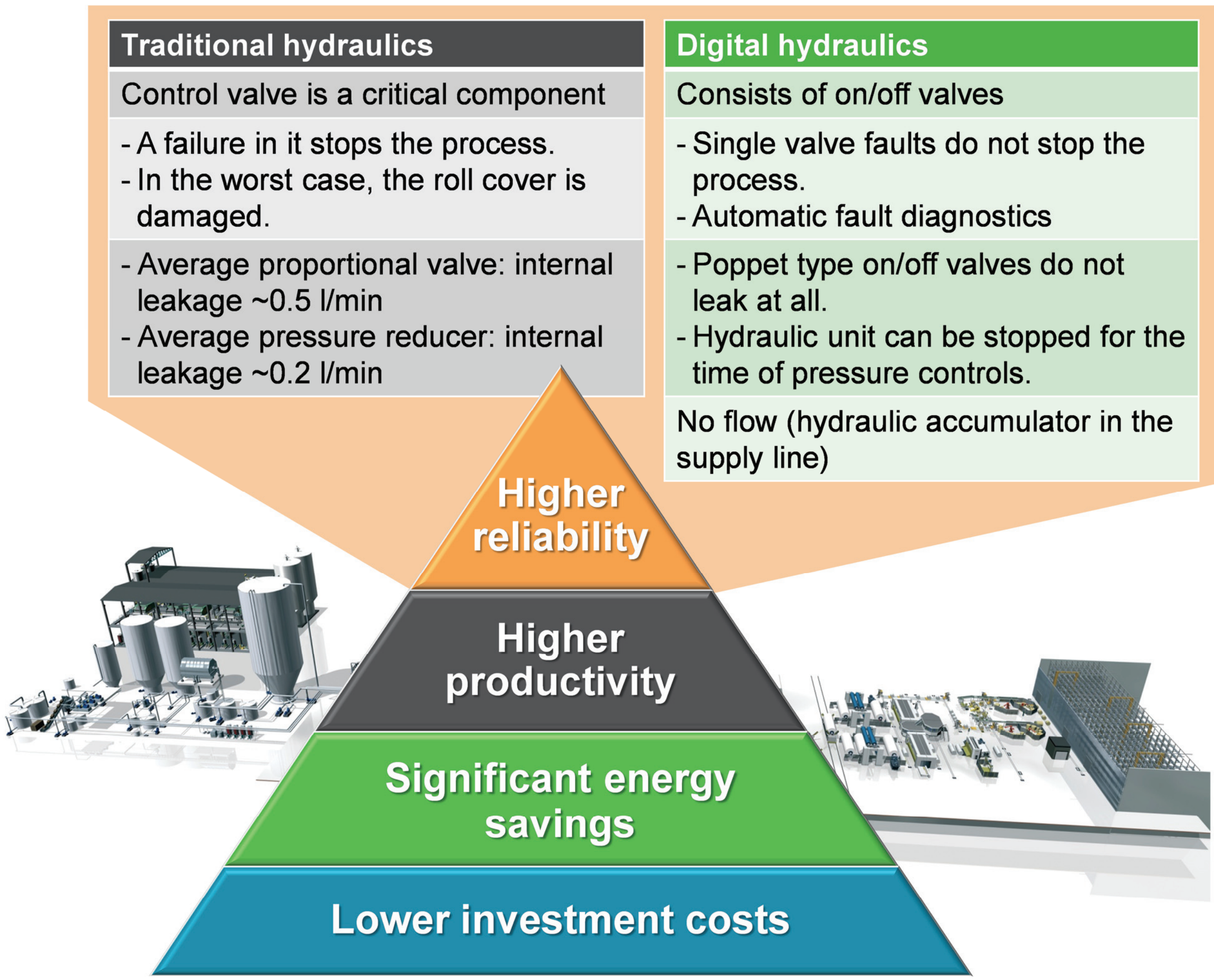


Figure 16. Digital hydraulics are superior in several ways to conventional analog hydraulics, especially reliability.

Converting from pneumatics to digital hydraulics

Many mills are converting older pneumatic loaded presses to more powerful hydraulic controls. However, when doing this, consideration must be taken not to overload the existing hydraulic power unit. In many cases, the extra load on the HPU can cause the oil to heat almost to boiling temperature. Therefore part of the rebuild expense – with traditional hydraulic controls – frequently includes a large HPU, a large oil tank, heat exchangers and pumps. This adds to the total installed cost.

On the other hand, when upgrading from pneumatic to digital hydraulics, things are different. According to Byron Muhs, Product Manager – Press for Valmet, "Upgrading your press from air rides or pneumatic cylinders to a solid hydraulic loading system is very easy and inexpensive with digital hydraulics as compared to traditional hydraulic unit upgrades. This makes it a lower cost." According to Byron, the HPU required for digital hydraulics is only 1/4 the size of a traditional HPU – mainly because the oil does not heat up nearly as much as with traditional hydraulic cylinders. Thus the smaller oil tank, lack of heat exchangers and fewer pumps – because you're not having to cool all that oil.

Byron further states, "Controls are the biggest unexpected downtime in a pulp, paper or board mill today. Mills cannot easily find knowledgeable E&I personnel. Digital hydraulics both reduces the troubleshooting as well as eliminates the knowledge needed to keep a proportional valve running."

Summary

The main benefits of the digital hydraulics as compared to conventional analog proportional valves are in energy reduction and reliability. Additional benefits include higher productivity, a lower purchase price, reduced spares cost, space savings, less field piping, temperature resistance and speed and accuracy of control.

Digital hydraulic control was proven to fulfill the requirements of paper machine applications such as calendar movement and nip loading control, with rapid change from flow to pressure control and no pressure overshooting. This is important because the calender must close as quickly as possible yet overshooting the target pressure can damage the roll cover.

The technology can be used and has been proven to be functional in all paper machine applications. It is especially important when converting pneumatic to hydraulic controls. Development continues, especially in making the control system and wiring simpler.

This white paper combines technical information obtained from Valmet personnel and published Valmet articles and papers.

Valmet provides competitive technologies and services to the pulp, energy and paper industries. Valmet's pulp, paper and power professionals specialize in processes, machinery, equipment, services, paper machine clothing and filter fabrics. Our offering and experience cover the entire process life cycle including new production lines, rebuilds and services.

We are committed to moving our customers' performance forward.