The Evolution of Process Automation: The Past, The Present, and The Future
- A Visionary Treatise -

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ABSTRACT

This paper traces the evolution of process automation for quality management from the humble roots of the first peaceful use of the atomic energy to present the state of process automation with a visionary look into the future. The various milestones in this evolutionary journey of quality management systems changed the nature, the impact, and the role of QCS (quality control system) as a result of technological developments, industry needs and requirements, and to a large extend business and market environment. The great entrepreneurial beginnings followed by periods of commoditization and renewals are examined through the various characteristic periods. Questions are posed about the future trajectory for measurements, various aspects of controls, cybersecurity, service, standards, and finally Industry 4.0.

As examples of the development path, the paper presents an insightful treatise of measurement principles and control algorithms in each major period of the evolution of paper machine control systems.

INTRODUCTION

At the heart of a paper machine control system is the so-called QCS that stands for "quality control system". A major part of QCS functionality is actually measurement activity. In fact, the QCS has been perceived as a mostly "gauging solution" for a long time (Nuyan & Long, 2007). Perhaps, a more accurate designation would have been QMCS, or the "quality measurement and control system" to reflect the focus and perceived value for the first 50-60 years if its history. This is certainly changing now. In general, the key to successful control is the measurements, in particular, the key to quality management on paper machines are the quality measurements along with a handful of process measurements such as flow, consistency, speed, and pressure transmitters installed throughout the paper process. Thus, the viewpoint of this paper is various aspects of process control for quality management on a paper machine including quality and process measurements, the associated controls, actuators, online and offline process analysis, control room, advanced control, Industry 4.0[1] solutions, and finally the progress towards the autonomous mill.

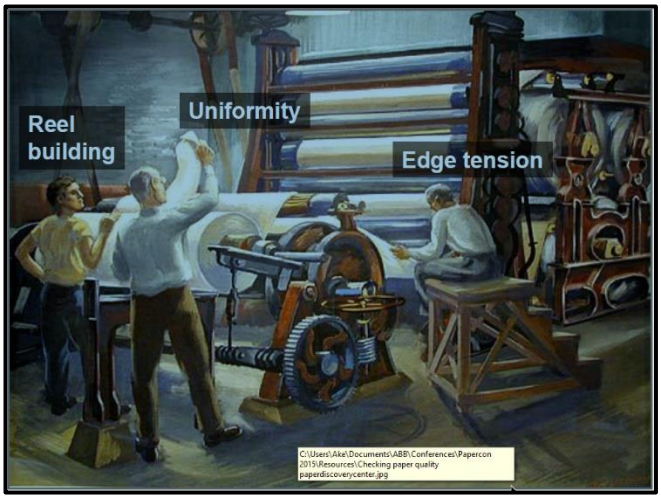

Figure 1: Papermaking challenges have not changed, only how you deal with it has-picture from (Hellström, 2015)

The challenge for papermakers has always been the uniformity of the paper produced (Leaver & Scott, 1998). Complicating the achievement of uniformity in all three dimensions, machine, cross-machine, and z-directions, is the requirement for high production rate. The profitability of the mill is largely dependent on these two factors. The goals of uniformity and high production rate are further compounded by the

[1] Industry 4.0 refers to the intelligent networking of machines and processes for industry with the help of information and communication technology. (PIMA IT Infrastructure CIG, 2020). The core technology for Industry 4.0 is the Internet not the computer.

runnability and transition management requirements. Paper breaks are costly and must be avoided. Grade changes can be long, destabilizing, and costly to recover from. Similarly, material and energy usage must be kept at as low level as possible to satisfy the cost side of the profitability equation. How some of these challenged were dealt with, some 50-60 years ago, is nicely depicted in Figure 1 (Hellström, 2015). Some of these practices continued even after the measurements were invented and methods developed to quantify the properties accurately and objectively. On this subject, Eric Leaver reports in his memoirs describing his inventions and his experiences as an entrepreneur (Leaver & Scott, 1998) as follows: "In those days, the methods for checking how a paper machine was running were, to say the least, primitive. To inspect the open unsupported draw between the couch and the first press, the machine tender would simply lift his hand under the running web to feel the tension. … The uniformity of the reels was checked by the backtender, who struck the reels with a small bat across their width as they wound. Backtenders claimed they could assess the uniformity simply by the sounds the reels made when hit. Consolidated Paper's Grand Mere Laboratory later automated this process by developing the Backtender's Friend. But automation was not easily accepted. I remember a backtender in Baie Comeau telling me that they did not need all this newfangled measurement and control equipment. After all, they have been making paper for 200 years without it – All they need was a bat. Some mill managers at the time agreed with him".

With the above challenges in mind including the resistance to accept automation, let us first explore the different development periods in the history of paper machine automation. As in any successful control, the measurements are of key importance. Without good measurements, it is hard to think of good control strategies.

THE ANALOG PERIOD - A PEACEFUL USE OF THE ATOM AND THE EMERGENCE OF QCS

In the late 1940's after World War II, a number of people were trying to discover peaceful uses of the atomic energy. According to (Leaver & Scott, 1998), most probably, the first companies to supply beta gauges were Frieseke & Hoephner in Erlangen, Germany and Tracerlab in Boston, Massachusetts. Others soon followed, however. A license was obtained by Curtiss-Wright Corp to sell F&H gauge in the United States (Leaver, 1990). The first installation of the Tracerlab beta gauge was in 1948 at the Continental Paper Co. Ridgefield Park, NJ mill (Hellström, 2015). The Chope brothers, who had worked for Tracerlab, left it, decided in 1950 to produce for industry a laboratory measuring device using radioactive Strontium-90, and set up Industrial Nucleonics, in Columbus, OH.

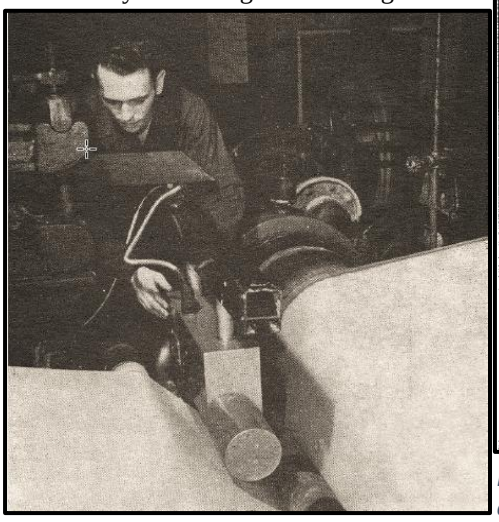

Figure 2: The 1952 beta gauge installed at Don Valley Paper Co., in Toronto.

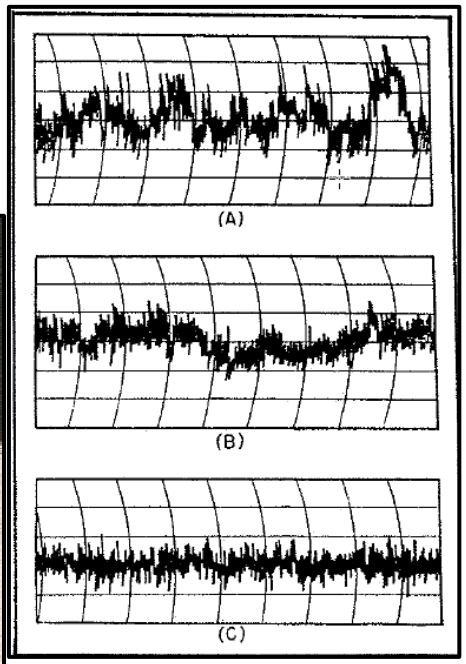

Figure 3: First documented basis weight control (1952), (A) No control, (B) Manual, (C) Closed-loop control. Each subdivision on the graphs corresponds to five pounds of weight.

In the meantime, in Canada, a group of scientists and engineers[2] left the Atomic Energy Commission of Canada (AECL) in 1948 and organized their own company that same year, Isotope Products Ltd in Oakville, ON. After considerable research, they were able to install, by early 1952, a radio-

[2] Don Brunton and some associates

active isotope-based beta gauge at the Don Valley Paper Co., in Toronto, ON, and later that year they tried and succeeded in automatic basis weight control using the beta gauge output as feedback signal (Leighton, 1952). Figure 2 shows the single point measurement installed after the wet press, and Figure 3 compares the results of closed loop control (C) with manual (B) and no control (A). In closed-loop control, the system was able to hold the 120-lb sheet within 2 lbs. while with no control (A), the graph shows 10 lbs. wet-streaks and slow oscillations. With manual control, operators are able to contain the variations to only 5-lbs. This was the first documented basis weight control in the machine direction (Lang, 2015). Two interesting aspects of the closed loop automatic basis weight control are noteworthy: The gauge was installed at the wet-end (a) to take advantage of higher sensitivity as the sheet was five times heavier than at the dry-end, and (b) because of the shorter time between the measurement and correction points.

Figure 4: The first profiling beta gauge on a scanning frame installed in 1954, (Hellström, 2015)

By 1954, Industrial Nucleonics installed a beta gauge on a scanning frame at the Champion International CO., in Lawrence, MA (Smith, 1954). The gauge scanned 166-inch sheet in approximately 4 minutes. This allowed continuous measurements, both "linearly" (in the machine direction) and across the width. Scan averages were used in a feedback loop to control the stock valve. This is the first documented profiling measurement system with closed-loop MD control using scan averages (Hellström, 2015). They have also introduced a contacting radio frequency (RF) moisture sensor for use on a scanning frame, the Moistron, enabling the company to measure and control online weight and moisture in 1960.

Parallel to these developments in the early '50's, Isotope Products was interested in a moisture measurement (Leighton, 1974). E.B. Eddy Co. in Hull, Quebec had already developed a moisture sensor that used the electrical resistance of paper to a 60-Hertz alternating current (Leaver, 1990). In 1955, they signed an agreement with E.B. Eddy Co., developed it for use on an O-frame for the measurement and control of moisture content. By 1956, the addition of moisture sensor called Aquatel enabled them to offer a weight and moisture measurements on a scanning frame with closed-loop control capability; i.e a combination system (Ott, 1958).

In 1957, Isotope Products was purchased by the Industrial Products Group of Curtiss-Wright Corp. which in turn was purchased in 1964 by Electronic Associates of Canada[3]. In the ensuing 3-4 years, they made the acquired sensors more robust and added a number of online sensing capabilities to its portfolio including caliper, two microwave moisture sensors, formation, reel hardness, and opacity. Infrared moisture sensor and a contacting combination sensor that could measure tri-stimulus color, brightness, and opacity followed suit shortly after.

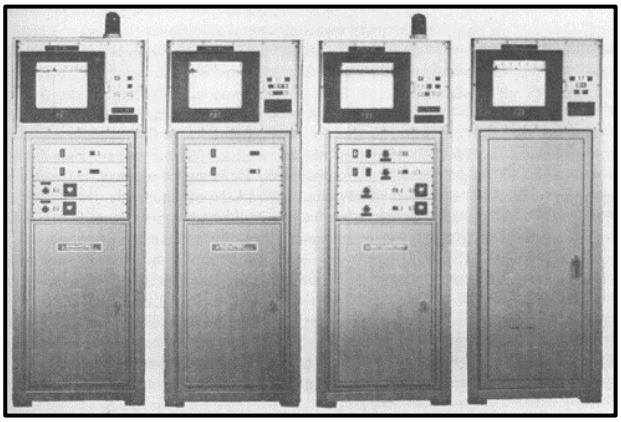

Figure 5: An early analog paper machine control system before computerization (Leaver & Scott, 1998)

[3] Founded by Eric Leaver in 1946 as an engineering company that, in1963, added the words "of Canada" to its corporate title, became publicly traded, and formed a subsidiary in the US the following year, Electronic Automation Systems Inc. (The Electronics Communicator, 1972).

Hence, through the above developments by different group of researchers and developers, by mid-to-late 1960's, the main paper properties of immediate interest to papermakers could be measured and some could even be controlled.

Figure 6: Series E analog control system before computerization

However, the quality control system (QCS) technology platform was still analog as shown in Figure 5 and Figure 6. In those years, a typical paper machine control system would use single-loop analog controllers, X-Y plotters, relay logic, line shaft control, or possibly a sectionalized analog dc-drives (Bialkowski, 1988).

The analog platform was very limiting especially for controls. The flexibility was simply not there to implement suitable control strategies for the paper process. The paper quality control dynamics has long deadtimes between measurement and actuation points. The proportional, integral, and derivative (PID) controllers were available in electronic or pneumatic hardware, but they were not suitable for the paper quality controls unless the deadtime could be handled with some clever hardware strategy. One such strategy was used in the Series E system (Figure 6) by using motor driven delay timers to inhibit multiple control actions until the response reached the scanner (Lang, 2015).

In a continuous-time process, long deadtimes introduce phase lag that is difficult to handle. One could also not address non-linearities and, most importantly, the interactions between process variables. The digital computer on the other hand, offer more freedom, flexibility, and computing power.

THE DAWN OF DIGITAL AGE

Computerized automation was already introduced to the pulp and paper industry with varying success in early 1960's. The first computerized paper machine control was installed in 1961 at Potlach Forest, Inc. in Idaho. The first digester control system was at Gulf States Paper in Alabama in 1962, and the initial application in Europe was in 1963 at the Enso-Gutzeit Oy. Kaukopaa Mills in Finland (Leiviskä, 1999). The first application at Potlach used a large, slow, and expensive business computer then available and relied on models of the process rather than measurements. Subsequently, IBM introduced its 1700 series to optimize trim operations at St. Anne and its 1800 series to directly control a couple of machines at Consolidated Papers Inc. in Wisconsin (Leaver & Scott, 1998). The introduction of minicomputers around 1964 made the computerization in paper mills very attractive although it was not until the microprocessors were available in the early 70's when computerization increased rapidly and had a major impact to the automation of pulp and paper processes. The early systems primarily used supervisory control and changed the setpoint of an external analog controller. With the advent of instrumentation, computers started executing the low-level regulation and directly outputting it to the field actuation devices. In other words, they became controllers. This is called direct digital control or DDC.

The first computerized quality control system for the measurement and control of a paper machine was developed by Measurex in 1968. The company was started at the beginning of the same year by David A. "Dave" Bossen. The company initially used the Hewlett Packard 2116B minicomputer with 16K of core memory and developed the MX1000 system. The first three systems were installed in 1969 on paper machines with different capacities and grades which proved the concept. Figure 7 shows MX 1000 installed in a paper mill (Bosson, 1978).

Figure 7: MX 1000 minicomputer based QCS, circa 1969, picture from (Bosson, 1978)

About the same time as the announcement of the first dedicated control system, Electronic Associates in Canada developed a hybrid basis weight and moisture control system with Beloit Corporation and installed it at the Bowater mill in Catawba in 1968. The following year, a similar system was installed at the International Paper mill in Androscoggin in Jay, Maine. These were hybrid systems with a computer attached for control purposes. Subsequently, they introduced a minicomputer based QCS system in 1971, called System 7000 (Ref1) which was exhibited it at CPPA and TAPPI the following year. Industrial Nucleonics followed with its own computer applications during this period which culminated in the introduction of the 1180 system (Ref2) in 1973-74[4]. Hence by early to mid-1970's, the digital system growth was well underway and accelerating already along with the developments of new sensors.

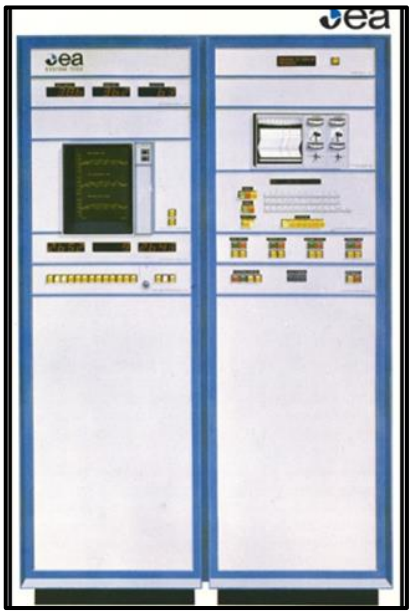

Figure 8: System 7000 (circa 1971) Typical Configuration

Two features of System 7000 system are noteworthy: (i) The system was modular in both hardware and software, (ii) A data bus was used between cabinets and modules. The system used a Varian 620/L minicomputer with 24K core memory and a 300 character per second paper tape reader (Radage, et al., 1972). A typical configuration with two cabinets is shown in Figure 8.

The development of microprocessors in the early seventies revolutionized process control. The next step in the evolution of paper machine control systems was to adopt microprocessor-based designs. The central processing confined in a minicomputer could now be distributed to several microprocessors that were networked. This significantly increased the processing power and memory capacity. It also allowed for scalability. The first distributed[5] and microprocessor-based systems were MX 2000 (Ref3) and Sentry 100 (Ref1) in mid-seventies.

During this period, it was possible to use modern control concepts in paper machine measurement and control applications. The QCS suppliers implemented model-based algorithms in their "packaged" offering. Machine direction control of major quality variables like basis weight and moisture were designed using primarily deadtime compensation algorithms. Two common deadtime compensators dominated the market: The Smith Predictor (or the modified version) sometimes also referred to as "model reference control" and Dahlin Controller (Dahlin, 1968). The deadtime compensation algorithms often recalculated and updated the model parameters every execution cycle based on machine geometry and current process values. This kind of adaptation of the process model minimizes model errors and induces some level of robustness into the control loop and its performance. An additional layer of robustness was also introduced by establishing upper and lower limits to future trajectories of the controlled variables.

MD controls were mostly single loop with feedforward and decoupling features to deal with interactive nature of pulp and paper processes. Basis weight and moisture interactions were considered by controlling the dry weight (basis weight-water weight) rather than basis weight. Non-linear compensation and use of deadband were also implemented although sometimes with questionable value (Bialkowski, 1988). In addition to the above features, concepts such as cascading loops and ratio control were now possible at nominal cost (Sell (Chair), 1995). Special paper machine applications like steam pressure letdown for more effective and efficient break recovery, handling of

[4] From the company's 1974 Annual Report

[5] "Distributed" refers to a modular architecture where each scanner and its measurements and process interfaces are managed by a separate computing module. Another milestone development in distributed measurement system (DMS) came in 1995 where each sensor module and the scanning device were managed by its own processor(s) rendering the designation of "smart sensors"

grade dependency automatically, and some optimization algorithms were easily implemented in the evolving digital platforms.

After the publication of a seminal paper on self-tuning regulators (Åström & Wittenmark, 1973), a flurry of activities by researchers led to the enlargement and extensions of the concept and development of suitable applications in various industries including first for the pulp processes and later on the paper machine. For example, a multivariable self-tuning regulator with a variable forgetting factor was developed in 1981 and installed in a newsprint mill in Ontario the following year for the control of weight and moisture (Wong, et al., 1983). Another

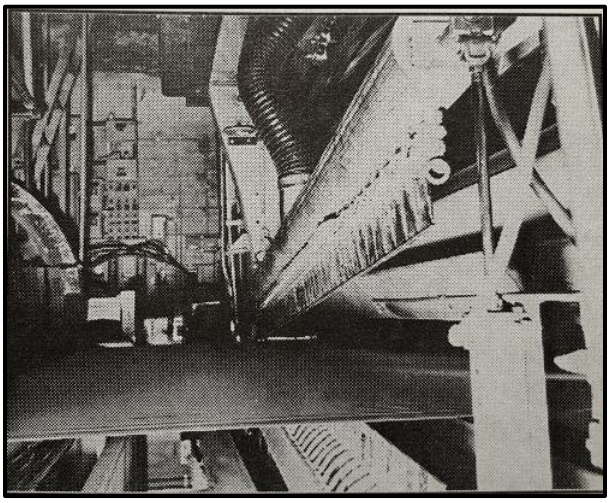

Figure 10: Calitrol air showers for the control of caliper, picture from (Leaver & Scott, 1998)

Figure 9: Online caliper gauge (Calitel) installed at Consolidated Paper Inc. of Wisconsin Rapid mill for CD control purposes, picture from (Consolidated News, 1964)

application on a linerboard machine attempted for optimum constrained control of moisture (Sikora, 1983). The moisture control problem is especially suited for adaptive control due to the nonlinearities and changing nature of the process. Another self-tuning moisture control system was field tested at Fox River Paper Company in Appleton, WI with improved results of the final sheet moisture (Fjeld & Wilhelm, 1981). These attempts remained by and large as prototypes, however, and did not attain widespread commercial use.

Although first weight and moisture profiling systems were installed in 1954, successful CD control applications did not appear until early 1970's. Some prototype applications actually were already undertaken in mid-60's. Also in mid-sixties, Consolidated Papers Inc. of Wisconsin Rapids, the largest fine paper producer in the US at that time had invented, built, and installed an online caliper gauge and a means of correcting caliper while still on the machine (Consolidated News, 1964). Electronic Associates of Canada licensed both of these devices, manufactured, and sold them under the tradename of Calitel (caliper gauge) and Calitron (air showers for CD control).

Caliper measurement and control was a much-needed addition to the measurement and control of paper, but there were some difficulties because of the contacting nature of the measurement. This required some further development effort before automatic CD control of caliper achieved a widespread-use status and eventually replaced another related CD control, that of reel hardness that had quickly become popular in CD control of calender stack in newsprint mills. Despite the caliper measurement difficulties, crown/tilt control was achieved prior to full control.

The first successful CD controls that the authors are aware of is the control of reel hardness in 1970 at the Consolidated-Bathurst Wayagamack mill. In the late sixties, Consolidated-Bathurst Research in Grand'Mere Quebec developed the "Backtender's Friend" which sensed the reel hardness profile much like the backtender's "stick" that helped the operator to control reel build manually. This invention (Knight & Blenes, 1974)was followed in 1979 by the all-electric remote calender air valve operating system marketed as Backtender's Beacon (Snider, 1990) facilitating automatic CD control at the Wayagamack mill. In the early eighties, the company also developed an actuator system utilizing a row of high-frequency electrical induction elements located in close proximity to the calender roll to heat it locally (Aniserowicz, et al., 1997). All three inventions were subsequently

licensed by QCS suppliers (Ref 1-3) and commercialized for widespread use starting in 1973 with reel hardness measurement (Ref 1).

CD basis weight control technology also dates back to late '60's and early '70's (Bialkowski, 1988) although control of CD weight is a much more complicated problem than CD caliper or hardness due to varying response shapes depending on the application and machine running conditions that were not systematically studied for some time. An early example from mid to late '60's is the work on slice segment control on the fine paper machine at the Howard Paper's Dayton mill. Another example is at a mill in Belgium where a large number of pipes were installed in the headbox in a line matching the slice opening and fed with manually adjustable fresh or white water (Leaver & Scott, 1998). It is interesting to note that, according to Leaver who visited both sites, the Dayton work was using an analog computer to model the complex segment interactions but did not succeed while the Belgium system with dilution pipes was functioning but, according to Leaver, did not lead to any kind of commercialization as an automation product. One reason the dilution idea did not move forward was the lack of enthusiasm in the industry at that time, Leaver speculates (Leaver & Scott, 1998). "Many paper-manufacturing executives of the day did not think control technology was the way to go". They were not entirely right, of course. While, from a control perspective, the dilution case is somewhat easier to solve than the slice, this idea has eventually led to technology change in headbox design and was implemented with automated CD control.

There were several reasons for the late entry of automatic CD weight controls into the paper machine control system portfolio. First, it took some time to develop CD actuators that could reliably operate in a harsh environment and would be trusted by paper makers for deployment. Another major reason is the lack of understanding of the complex interactions of slice actuators and the underlying mechanisms of how they change with process conditions. Pre-requisites for developing good models were also lacking at that time: an accurate measurement of the slice positions and adequate resolution of the quality profiles. For these reasons it wasn't until the landmark STFI research was published in 1978 (Erikson, et al., 1978), meaningful and robust CD weight controls with constraint handling could be designed. Indeed, after some prototype installation in Sweden, the STFI strategy was licensed by a North American QCS supplier (Ref1) by early 1980's and productionized for commercial use by 1983 for all CD control applications in their portfolio (Elliot, 1984).

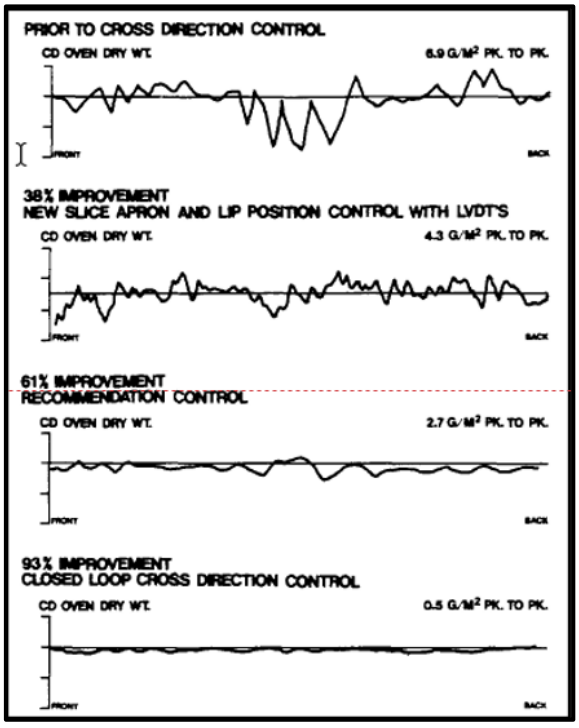

Figure 11: Closed-loop CD basis weight control results from the stage-wise application of the 1st North American installation of STFI optimization (circa 1983-84)

At the center of the STFI CD control method is the use of a high-resolution unit step response in the controller, the ability to predict it online based on the process conditions, and the optimization concept using a performance index that could accommodate various performance goals including constraints. The results of CD basis weight control from the first application of STFI method in North America designed into a packaged QCS are shown Figure 11 (Nuyan, 1986).

It is interesting to note the impact of each phase of control implementation to the results shown in Figure 11. The commissioning in this mill was executed stage wise with a recommendation phase where the QCS system optimized the profile by recommending slice-screw position change to a small set of actuators with the biggest impact which the operator would carry out manually. This short period allowed operators to gain confidence and provided an opportunity to see the results before closing the loop.

In early 1985, another basis weight control solution (Ref2) considering the cross-coupling and the slice bending constraint in a quadratic penalty function was installed at the Union Camp Savannah mill which subsequently was also productionized for commercial use (Chen & Wilhelm, Jr., 1986). This solution was enhanced later by adaptively refreshing the actuator response using the self-tuning estimation technique (Chen, et al., 1986) employed earlier for MD moisture control. After the 1976 introduction of CD caliper and moisture controls, Measurex announced their first CD weight control using a different approach in 1979 (Factbook, 1989).

The development of CD actuators (profilers) also accelerated throughout '80's in parallel and as a prerequisite to the advances made in control technology. In addition to the packaged turnkey QCS providers, standalone 3rd party companies specializing in profilers emerged in the market and provided much needed innovation in this field.

Hence the stage was set in early '80's for widespread use of CD controls that indeed took place the rest of the decade into the '90's and gave a new impetus to the growth of QCS systems. The uniformity results achieved contributed significantly to the quality of paper, board, and tissue. Product uniformity meant better runnability of the machine and downstream operations. Cost savings and productivity increases were additional benefits and combined together, these benefits had a noticeable impact in the profitability of the mill. By the end of 1990's, most paper machines around the world were equipped with at least one or more independent CD controls.

The fast and significant progress of the packaged systems in the '70's and '80's was made possible also because of the developments in the instrumentation in the paper mill. The emergence of distributed control systems (DCS) is attributed to the original idea of replacing analog controllers with digital distributed controls when the 8-bit microprocessor became available in the mid 1970's (Bialkowski, 1988). With the advent of processors and graphic displays, computer-based algorithms replaced the analog controllers. The introduction of DCS allowed traditional relay controls, interlocks, alarm handling, event logging, trending, and other tasks to be done in DCS's. The ease of interconnection and reconfiguration were attractive features that accelerated the digitalization in the paper mill. Central to the DCS software architecture was the idea of function blocks. The function blocks are similar to the subroutines and associated tables in the packaged systems but much more sophisticated architecturally to allow easy utilization in computer-aided design, configuration, and execution of tasks. Since processing is distributed, digital communication between all computing units, controllers, display processors, alarm handlers, and other computing units played an important role in the extended use of computers in the automation of paper mills.

With the advent of the digital algorithms, it became clear that some analysis, commissioning, reporting and documentation tools would be needed to aid in the commissioning, performance monitoring, and troubleshooting of online measurements and control systems. This was nowhere more evident than in the complex world of CD controls where stability and robustness of the system imposed certain accuracy requirements to key commissioning parameters like the mapping and response shapes as well as adequate measurement resolution. The early tools in the late '60's and '70's for the analysis of response shapes and preparation of response parameters for the online system was done off-line with computer programs that would be mostly written in Fortran that ran on mainframes or minicomputers. Once the personal computers were available and became the engineers' tool, more tools were developed by the QCS suppliers to satisfy the need. By mid to late 80's, the tools landscape belonged mostly to suppliers, and tools were designed by them for their specific purposes (Fu, et al., 2001). At the same time, more general-purpose applications for the personal computer including spreadsheet programs were starting to become part of the toolbox for the automation needs in the P&P industry.

THE INTEGRATED PERIOD

The computerization of measurement, control, and information activities in a paper mill proceeded based on the need and how that need could be best satisfied. Mill executives naturally consider a lot of factors when they make investment decisions. By the second half of 80's, there were many computer-based solutions offered by many suppliers, performing various different functions such as process controls, machine controls, quality controls, drive controls, trim controls, reporting of production information, and other automation needs. These functions were sometimes overlapping in different suppliers' offerings. Mill executives' and technologists' decision-making

tendencies at that time forced them to choose the "best of the breed". Most often, what was perceived to be best of breed in one automation function could be different than the best-of-breed in another automation function. As a result, it was not unusual in a mill that the various automation functions belonged to half a dozen or more automation suppliers. The term "islands of automation" was coined to this evolutionary state in the automation of industrial processes.

Multiple islands of automation presented a lot of challenges for the mills, sometimes difficult and costly to resolve. Perhaps the most important ones were associated with the suppliers of these functions having different computing platforms, i.e., hardware and software environment and the fact that different suppliers came from different technical and business cultures. As a result, spare parts management, maintenance, and training requirements, and even performance focus as pointed out passionately in (Bialkowski, 1988) were a major issue. Different technical cultures were very likely to have different control and performance objectives.

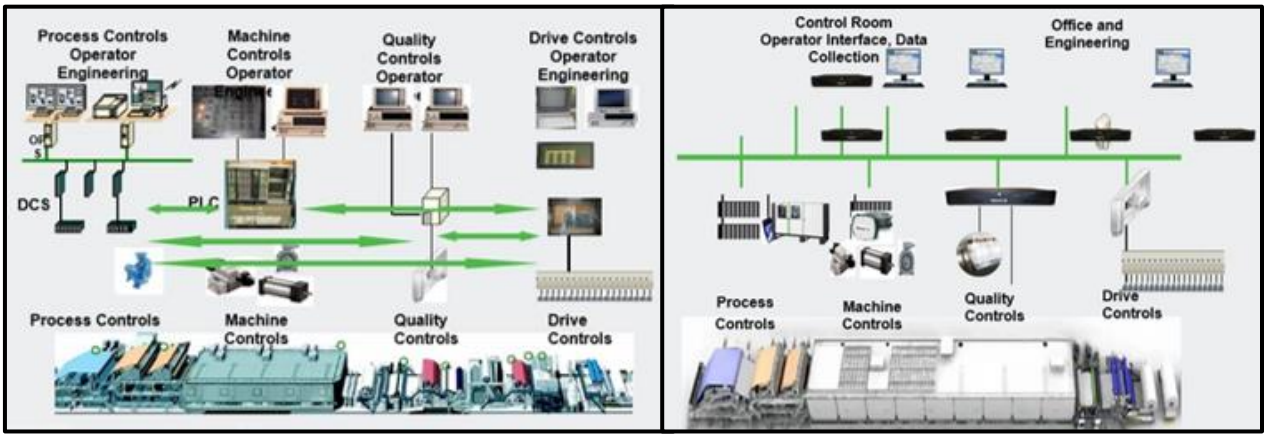

Figure 12: Islands of automation, limited connectivity via various datalinks (left), and integrated approach (right) using the same hardware, software, and engineering environment on a common data highway

In the "islands-of-automation" approach shown in Figure 12 (left), the different suppliers' computing platforms were connected with various and often proprietary datalinks generally serving limited purposes. All of the packaged systems were coined the term 'black box" since you did not have easy access and visibility to the programs running the system nor the applications controlling their processes. If a problem developed in the mill, blaming ("finger-pointing") each other's system became a common occurrence. These problems eventually became so frequent and critical that the industry and the decision-making processes forced the trend towards a more integrated approach.

Initially, integration meant different things to different suppliers and paper producers. Nevertheless, the integration concept that would best serve the industry was eventually envisioned to more or less look like as shown in Figure 12 (right) where all process control functions were executed within the same hardware, software, and engineering environment, and all computing modules were in a standard network with the capability to access and share data. Different topologies and level of integration appeared in the market during this period including stage-wise realization of a "native" integration concept for all automation functions as defined above and shown in Figure 12.

The distributed control system was, in many ways, the obvious choice for further development and the integration starting point of other control and information functions. While the early DCS's had to struggle with the cost per loop, there was no doubt that the inherent flexibility and power of the DCS would lead to their dominance of the instrumentation world (Nuyan & Long, 2007). By late 80's DCS had received widespread acceptance. While processing was distributed, they allowed centralization of user activities in a control room providing overall view of the process and operability on controllers and other devices. They also allowed integration of control and information functions, easy interconnection and re-configuration of plant controls, standardization of hardware and software technology for easier maintenance and expansion, application software open to the user, and connectivity for integration of data acquisition and control, both horizontally and vertically (Brewster, 1989).

Hence, there was growing pressure to integrate QCS with DCS already in the mid-to-late '80's. By late 1980's, the so-called "single window" solutions started appearing in the market. Single window referred to the integration of user interface (control room) onto the DCS platform so that operators would use the DCS user interface for both the DCS and QCS. Other QCS functions including sometimes an engineering terminal stayed in the dedicated systems of the various suppliers. Next step was porting over other QCS applications including MD controls. Finally, when the last remaining QCS application, CD controls, were implemented on a DCS platform, the integration was complete. It took some time to accomplish the final step (Brewster, 1989) as the DCS was lacking the data structures and tools to efficiently deal with array (profiles) type structures as a "native" type. While they were in development, suppliers continued integrating other control and information functions onto the DCS platform.

Naturally during the integration period, suppliers, sometimes in collaboration with paper and pulp mills, continued to make improvements to their existing systems and introduced new applications to help paper manufacturers make better paper, better decisions, and better management of their assets. A significant development for MD controls was the introduction of wet-end controls after the invention of on-line low-consistency measurement (Kortelainen, et al., 1989). Mills could now implement white water and headbox ash consistency measurement with the accompanying controls (Rantala, et al., 1994). Shortly after this, it was possible to implement multivariable control algorithms which also benefited significantly from the inclusion of wet-end controls into the multivariable controller. In the smaller domain of MD controls, this was indeed another integration action of wet-end and dry-end (Lang, et al., 1999) . The sensor improvements continued especially with respect to their resolution that had started in mid to late '80's. Adequate profile resolution is a prerequisite to optimum CD controls (Nuyan, 1986) as even the early CD controls for highly coupled process responses would need to do. By 1990, major QCS suppliers had achieved adequately high-resolution profile measurements for CD control with scanning technology often requiring sensor redesign to balance sufficiently high flux in a smaller spot size moving at faster speeds with adequate statistical significance for each databox (Nuyan & McNelles, 1990).

While some form of multivariable CD controls was already in existence before the integrated period, the multiple-input multiple-output (MIMO) profile control based on multivariable model predictive control (MMPC) entered the scene during the integrated period when the computing power requirements were met by the technology used for the automation platform.

FULL SHEET IMAGING

The QCS was born with the invention of quality sensors that were capable of producing either continuous measurements at a fixed cross-direction position or along a diagonal path created by the moving sheet as the sensors traversed from one edge of the sheet to the other at a much lower speed than the sheet itself. As a result, in either mode, scanning, or fixed point, they only saw a tiny fraction of the sheet. In the scanning mode, only about 1% to 1.5%, at best, of the sheet was measured depending on the ratio of wire speed to scanning speed (Figiel, et al., 2010). The MD and CD controls, therefore, are based on the best estimate inferred from the properties as seen in a tiny fraction of the sheet. So, the holy grail of the gauging world, for at least 4-5 decades, has been to develop full sheet measurements that did not have to mechanically scan to cover more of the sheet.

The quest for a non-scanning measurement started in the early '80s by research institutes, research departments of paper producers, the major North American QCS suppliers, and subsequently also by European manufacturers of gauging systems. Two types of measurement systems were the target of early research (Nuyan, 1988):

(i) by scanning web quickly through multiple stationary sensors, and
(ii) by viewing the sheet remotely similar to a concept that some machine vision systems also adopted (an example discussed later shown in Figure 13.

The multiple stationary sensing concept was already suggested in a patent filed in 1971 (Tirkkonen, 1971) for measuring basis weight and moisture. In this suggestion, the measuring system consisted of a set of tubes mounted along the width and on both sides of the web for distributing and detecting transmitted light. An extended version of

this concept is described in (Mactaggart, 1982) for measuring color, brightness, and opacity profiles simultaneously. In this arrangement, light from a plurality of sources located along the width of a moving web was directed towards and through the sheet. Light reflected from and transmitted through the sheet is then conveyed by a plurality of light pipes on the illumination side and the opposite side to their respective detectors on each side of the web. The detectors where than presented with electronically scanned band-passed slices of the spectrum for the determination of color brightness, and opacity. In addition, by multiplexing the output of both detectors, these parameters could be profiled.

Using electronic scanning and multiplexing concepts, other prototypes were built in the '80's, for weight and moisture also, but none of these attempts made it to sustainable products. These early designs had limitations, sometimes purely in terms of cost against perceived benefit, to sustain a continuous presence in the market.

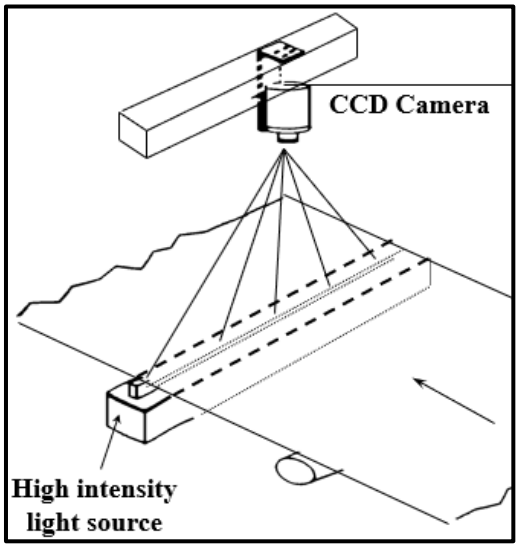

Figure 13 Viewing type formation sensor (Dufresne, 1988)

One of the early examples of the second kind by viewing the sheet remotely for some characteristic parameter is the measurement of formation with a linear CCD (charge coupled) array camera which detects the intensity of visible light from fluorescent tubes through the sheet (Dufresne, 1988). The concept is shown in Figure 13. Formation index was quantified as the RMS variation in the light transmitted through a given measurement cell size.

These efforts continued in the '90's (Waller, 2001). An interesting example from the late 90's is the use of an array of scintillating optical fibers positioned below the web in the cross direction to detect web-attenuated beta radiation emitted by a linear Kr85 beta source positioned above the web (Griffen, et al., 1998). After the proof of concept, a prototype was built with some modifications of the original concept.

Another example of fixed full sheet sensors in the late 90's is the water weight measurement at the wet end (Garnett, 1998). Each sensor consists of a sending and grounding electrode embedded within an existing machine drainage foil under the wire. The electrodes establish a flux coupling with the sheet above the fabric and facilitates the measurement of conductivity of the stock which is correlated to the weight on top of the wire. Since the effective electrical properties of the furnish change with composition and temperature, the signal is compensated with an online reference sensor element measuring the electrical properties of white water doctored from the underside of the fabric (Waller, 2001) (Hagart-Alexander, et al., 2000). These sensors can be placed very close to each other in the CD for high-resolution profile measurement or at selected locations in MD down the table between the head box and dry-line to provide MD drainage profile (Hagart-Alexander, et al., 2000). Case studies reported in (Hu, et al., 1998) provided much insight into the drainage process and the possibility for tighter control of the white water system.

A good example of full sheet imaging by viewing sheet with multiple CCD cameras was introduced in the late 90's for the measurement of basis weight (AccuRay, 1997). In this design, an array of line scan cameras view a zone of the paper illuminated by high intensity incandescent lights with parabolic reflectors. The transmitted light filtered selectively in the visible and NIR (near infrared) portion of the electromagnetic spectrum yields mass distribution information (Pfeifer, et al., 1998). The system uses a unique data compression technique and a patented approach that tailors discrimination levels to camera pixel positions. Because light transmission differences exist within grades, the signal must be calibrated with a scanning gauge for accurate measurement. Typically, the system produces images with a CD resolution of 1 mm (Pfeifer, et al., 1998). Much insight was gained about MD and CD variability from the high-resolution images as reported in (Chen & Pfeifer, 1998).

One of the latest introductions of a full sheet measurement of paper was a press-section moisture measurement based on multiplicity of stationary sensors placed in an array across the machine (Fors, et al., 2003). This tool proved to be useful in start-ups, as a diagnostic tool, and as input to a number of applications including additional feedback

and feed-forward control, and as a full-sheet estimation tool at the real or any downstream locations where a downstream scanning sensor might be present (Fu & Nuyan, 2003). Subsequently, a dozen more systems were taken into operation, however as in the previous cases, it, too, did not find a widespread use as a commercial product.

In summary, there are no "non-scanning" or instantaneous measurement of paper properties that has gained widespread use and sustained a continuous presence in the market. There are still many challenges to be overcome including the perceived cost to benefit ratio to extend these and other technologies briefly discussed here to cover the whole range of paper properties, but there is still hope that this will be the next watershed event in the gauging world (Nuyan & Long, 2007).

THE PAST AND THE PRESENT

With this background, let us now summarize the past and present state of process control in paper mills and finally anticipate the future trajectory. Clearly, the measurement portfolio has widened very quickly after the introduction of nuclear weight sensors and eventually took a steady rate of progress in new quality sensor introductions. Along with basis weight, reel hardness, caliper, moisture at different md positions, optical properties such as color, opacity, brightness, and gloss, formation, total ash, and constituent ash were among the first group of measurements followed by direct coat weight, white water and headbox ash consistencies for wet-end control, fiber orientation, porosity, press moisture, forming section dewatering, coating gel-point, smoothness, roughness, non-nuclear basis weight for tissue, surface topology, crepe characteristics, color for tissue, and mechanical properties such as strength came subsequently. Although there are still challenges with measuring the mechanical properties, for example, it is also possible to build soft sensors for them. With the advent in measurement technologies and the apparent need, it is likely that reliable direct measurement of mechanical properties will also enter into the field.

The sensor improvements also took place over the 70-year history of QCS in step with the changing papermaking needs. There have been periods when major sensor upgrades were undertaken starting with micro pointing of sensors for high resolution measurements. Computer aided design facilitated design of optimum optical sensors with significantly improved performance and reliability. Same can be said for the improvements in contacting caliper sensors. Major improvements were done around the turn of the century to contacting caliper solution so they could measure reliably without causing problems in runnability, especially in high-speed newsprint, SC (super-calendered paper), and fine paper production.

The critical milestone for caliper measurement was to remove contact from at least one side of the sensor to avoid pinching and sheet breaks. This was first achieved in 1977 by means of a vacuum contact plate on the bottom side of the sheet and a top sensor component riding on an air bearing (AccuRay, 1978). Dual sided non-contacting laser beams were attempted in the early 1980s but had inaccuracies due to sheet control and alignment related issues. In 2004, an optical caliper sensor was introduced using laser caliper triangulation on one side and creating a stable reference on the opposite side for paper to ride on and thereby avoiding pinching (Graeffe & Nuyan, 2005). The new design techniques and availability of advanced components also allowed sophisticated new sensor design for properties like surface topography, new moisture sensors, and crepe characteristics in tissue manufacturing.

Turning to the controls, the first applications were single-variable controls for MD variables, first analog, and hence very limited. When digital computers came along, it was possible to implement model-based algorithms, but the difficulties remained in decoupling the highly interactive variables as the interactions could not be easily compensated for. This challenge was overcome with the introduction of model based multi-variable predictive controls that are now in widespread use. Today, MD control algorithms used in paper making processes are mature. They are also relatively robust, i.e., they can tolerate process changes without becoming unstable or oscillatory. Integration of wet-end and dry-end controls have enhanced the stability and robustness features and enabled a new level of performance.

More flexible control structures were also developed which allowed easy addition or changing of variables, including controlled or manipulated variables without re-configurating the control by simply adding new tags and/or modules to existing controls. This was not possible before.

CD controls started with hardness and caliper because of the early availability of trusted actuators and the easier process response characteristics both the dynamic and cross-direction responses. Successful CD weight control had to wait until reliable actuators were developed and the CD process understood and could be modeled. They followed a similar path from single variable to multi-variable model-based control. Today, multi-variable CD controls can also be considered mature.

On the system side, processing power and storage capacity was initially the challenge. In the past, most analysis was done off-line. Tools lacked however even for off-line analysis until personal computers, then laptops came into widespread use. Even then, data analysis required good import / export capabilities of the on-line system. In contrast, computational power is more than adequate at present, and the QCS applications are developed to allow modeling (both MD and CD modeling) where most analysis is done online, and in most cases, automatically.

The other important aspect of QCS operations today is the remote access capability which brings the control experts quickly for troubleshooting needs. The needed skills are virtually at a mill without any delay. Secure connections from home office to paper mill for remote access with multi-factor authentication are in place.

In general, mills have progressed in integrating their automation assets, however, there is still more progress needed in this area. Similarly, OPC has become, in most cases, the standard communication protocol between different suppliers although proprietary protocols still exist.

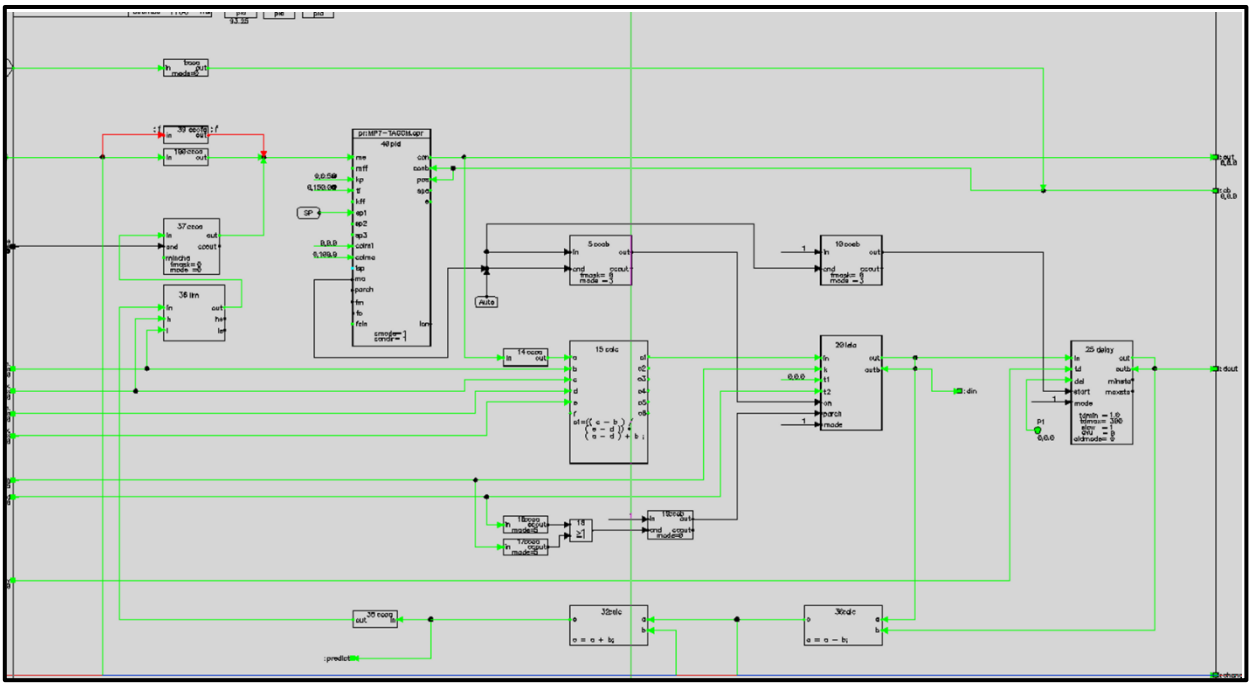

Figure 14: A typical control function block in the early 1990's

The control function blocks are central to the DCS model. They are pre-programmed calculations that accept numerous inputs of different types defined by the DCS architecture and can return one or more outputs in defined types. Like functions,

Before (early 1990's)	Present - Example MPC
- Developed by company A, by business division B, fpr Product C, likely for all geographic areas	- Developed by company A, for all its divisions, all products, all geographic areas
- Very specific to one type of application, for example paper machine MD weight control	- Widely used for all applications within the company, for example, energy business as well as paper quality controls
- Simple control, very little memory required	- advanced control, require large memory, nowadays possible
- Not very flexible, redesign when the process is different	- Flexible, different process can use the same algorithm
- Application maintained by a small group of people familiar with the product C	- Application can be maintained by many experts within the company

function block diagrams are one of the "program organization units (POU's)" used to develop a control algorithm. They are reusable within a program and can be stored in user-declared libraries for import into other control programs. Function blocks have also evolved including standardization effort by the International Electrotechnical Commission (IEC) (Babcock, 2016) (Wikipedia, 2005). A typical control function block early in the 1990's is shown in Figure 14. The accompanying table compares the attributes, the utilization, and the conditions of control function blocks in the past and the present. Clearly, the trend is that the core control blocks become more generic, more sophisticated, and more flexible.

THE FUTURE

There is no doubt sensor development will continue in the future perhaps only for critical new needs emerging in papermaking. At the same time soft sensors have also a role to play to enhance the existing measurement and control capabilities in paper production and possibly also fill the hole of missing measurement needs and / or provide estimated values between existing but slow measurements.

Camera-based machine vision system will continue their integration into the mill automation platform. Combined with scanning sensors they can already provide better prediction for full sheet measurements. Their role may increase if this trend continues.

We will also see more fiber characterization sensing online and incorporation into the controls.

The evolution of the control function block will naturally continue. Some thoughts for the future are outlined in the following table compared with the present state. One key feature noted as the last item in the future column is the emergence of universal standards. Many of the predicted features are possible if such standards find a widespread use among the producers of control systems which we predict will eventually take place.

Present - Example MPC	Future – Example MPC
- Developed by company A, for all its divisions, all products, all geographic areas	- Developed for all companies, all business, all products (Domain knowledge – Universal Dynamics 1988)
- Widely used for all applications within the company, for example, energy business as well as paper quality controls	- Widely used for all applications for all companies
- advanced control, require large memory, nowadays possible	- Advanced control, require large memory, with self diagnostic features (tell when something is wrong & where it is wrong)
- Flexible, different process can use the same algorithm	- Very flexible, for all process control applications
- Application can be maintained by many experts within the company	- Application can be maintained by any experts from many different companies
	- Such products developed under industrial standards, guidance by all players

The present trend for more analysis, visualization, and decision-making tools will accelerate. The recent introduction of variance partition analysis tool for reel statistical methods and the cross-direction mapping tools are good examples. Tools for learning, prediction, and knowledge generation / discovery may be in the pipeline as the industry is more in need of these than ever before. More capabilities through techniques like factorial analysis, multi-variable troubleshooting tools, and soft sensing techniques will appear. While these are fairly sophisticated methods, their user-interface must be simple with intuitive visualization and operation.

The biggest changes in the future are likely to come in the controls field and supporting tools for many activities including controls. The current MD and CD controls are already mature and fairly robust. However, they need attention and supervision with respect to their performance. They are expected to sustain their performance all the time, during upset conditions, unexpected disturbances, and new situations. Application of advanced process controls (APC) are already increasing rapidly especially in pulp and recovery processes. Use of optimizers are on the rise and tracking and scheduling applications in prototype installation with promising potential of profit improvements. This trend is now setting the stage towards semi-autonomous, and ultimately perhaps fully autonomous operation in pulp and paper. Data-driven learning and applications are also starting the appear at a good rate that will change the mill production landscape drastically.

Future advances in artificial intelligence (AI) are likely to play a major role in the push for more autonomy. The term AI in this context refers to the synthetic systems that can exhibit human-like intelligence (PIMA IT Infrastructure CIG, 2020). The current state of development towards AI in the industry can be described as the use of human reasoning as a guide to provide better services, tools, and controls rather than trying to achieve human-like intelligence. For example, at the present, there are tools for predictive maintenance that can predict equipment failures before they occur (asset management systems). This allows maintenance teams to take preventive actions and minimize downtime. In most cases, human intelligence finds the most appropriate actions and executes them. In other words, it is the human intelligence that closes the loop. The next steps may be gradual migration of what human intelligence does today to AI-driven systems in the future.

Similarly, the increased use of machine vision, pattern recognition, data analytics and voice recognition will allow more and more tasks requiring human intelligence to be performed by machines. Expert systems and neural network applications for learning are also part of the AI toolbox and are likely to find increased use in the pulp and paper industry.

As the tools get smarter in their decision-making capabilities and widen their knowledge domain and as the controls become smarter to be able to supervise their performance, there will be less reliance on human intelligence. This also means the industry will get closer to smart manufacturing also known as Industrial Internet of Things (IIoT).

Smart manufacturing concepts will impact another important manufacturing activity with the use of advanced analytics to optimize supply chain. By analyzing data on demand including inventory, order backlog, current transportation, and production schedules, smart manufacturing can optimize supply chain to reduce costs and improve efficiency.

The degree by which smart manufacturing can be achieved depends on more and more, and smarter and smarter tools, industrial connectivity, and a lot of data from various sources, mixed timelines and locations. The smart tools will facilitate multi-location optimization, remote monitoring, and follow-up. In this environment, cloud-hosted applications are likely to be a necessity.

Mill executives are worried about the retiring and skilled personnel and continue having limited success with new hires due to their lack of experience. This concern comes up in almost every TAPPI and PIMA organized events. The push towards more autonomous mills is seen as the answer for the future. With excellent connectivity, perhaps global control rooms can be realized as a result. Performance centers are already being established on the supplier side to help the mills.

Putting all this together, the future manufacturing environment has the attributes of what is now called Industry 4.0 in its future where the core technology is the Internet. Computers, as the core technology of Industry 3.0, brought us to the current manufacturing environment, and it is the Internet as the next layer of technology that will take us to the future and possibly to autonomous mills.

In this journey towards autonomy, it is easy to envision more and more setpoints being specified by various data-driven and cloud-hosted applications, machine vision and machine learning being applied to reduce field activities such as inspections, operators reacting on abnormal conditions and overseeing safe operations with the help of "companion automation" (Nuyan & Long, 2007) in initial stages, later only supervising and defining the intent, and eventually automation supervising the operations. Similarly, one can imagine specific performance and economic objectives being carried out by advanced process controls (APC); initially, the system alerting and advising on the best performance and economic operating point of the process, robots handling of hazardous field tasks, and eventually the system exerting 100% control in all situations without manual intervention. This target may be still too far into the future; however, the journey has certainly started.

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