Megabytes for metals: development of computer applications in the iron and steel industry

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The steel industry pioneered the use of computers for process control. By the mid 1960s, almost a fifth of the world's process control computers were installed in the steel industry. The present paper documents the development of direct digital control with emphasis on hot strip mill control, notably the installation at Llanwern using a GE 412 computer. Early applications of computers in areas such as electric arc furnace control and order handling are identified. Archive sources, government documents, interviews, correspondence and technical papers show the leading role of steel in developing online control. Marked differences in adoption rates are identified. Two-thirds of the early steel installations were in the USA. Britain and Italy were also early adopters. Jones & Laughlin and Inland of the USA, the Steel Company of Wales and Italsider were among the leading innovators.

Keywords: Steel industry, Computers, Development, Process control

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Control computers may someday be applied in almost all of the processes found in an integrated steel mill (Stout and Roberts, writing in 1960)[1]

Computers and steelmaking: a symbiotic relationship

Steel and computers grew up together. Steelmaking is older than is often supposed, and computers are certainly older than their modern image suggests. To put things in perspective, computers are the same age as the radical innovation of oxygen steelmaking that rapidly became the predominant steelmaking process during the 1960s.

The post-Second World War boom in steelmaking coincided with the rise in practical computing. The steel industry played a pioneering role in developing applications for the new computer technology. New capital equipment called for new control techniques, forcing developments in machine drives and controls, sensors and data acquisition technologies, all vital to exploitation of the growing power of electronic computing. Computer based innovation continues in steel, as cheap computer power has made large scale modelling and comprehensive data capture, analysis and storage possible. This extends to current developments: notably through process modelling of the whole sequence of steelmaking processes and online quality prediction.

Precursors

Just as there were precursors to modern steelmaking, such as crucible steel in the 19th century, there were also practical precursors to computing, notably Jacquard looms, invented in 1801, and mechanical developments by Babbage from 1822 onwards. Hollerith's punched cards and automatic tabulating machines were used for the American census of 1890. Zuse, the son of a Berlin civil servant, built a mechanical digital computer in his parent's living room in 1938. In 1943, Turing's team at Bletchley Park built the Colossus electronic computer, using vacuum tubes, for code breaking.[2]

It is hard to say where computer control of steel manufacture began. Punched cards were used for mill control before computers. The first 'computer controlled' installations used one punched data input card per slab. This card contained all the information required by the computer to roll one slab. Arguably the first card controlled mill was the universal slabbing mill feeding the Aliquippa continuous hot strip mill of Jones & Laughlin.[3] This pioneer installation had three distinctive features: the use of digital control; storage of the rolling schedule in a memory; and the first use of transistors in steel mill operation. Westinghouse Electric were responsible for both the drive motors and the control system.

The same approach was later used at Armco's plate mill at Houston, but here a computer stored the rolling model equations which predicted separating force, mill spring and screwdown settings for each pass using a

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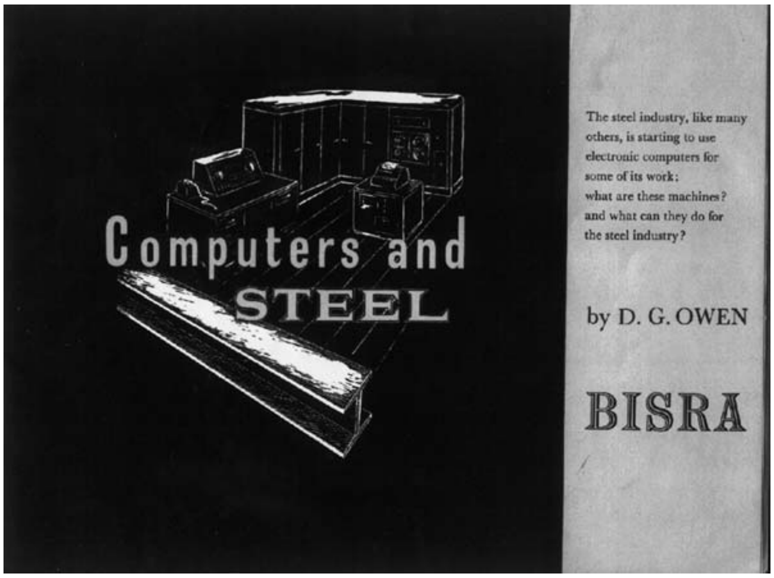


1 British Iron and Steel Research Association (BISRA) promoted computer use in UK steel industry from 1957 although their initial focus was on greater business efficiency: courtesy Corus Colors

Westinghouse Prodac 4449.[4] Part of the efficiency gain from computer operation arose from meticulous production planning and scheduling imposed by the time taken to load punched cards and the need to follow a preset sequence within each batch of cards. This installation was widely replicated, for instance at Italsider's Taranto works,[5] the Sollac, Sérémange slabbing mill in France and Dofasco's Hamilton works slabbing mill.

United States developments in card control were watched closely elsewhere in world steel. They alerted steelmakers to the potential of digital control. A Steel Company of Wales letter responding to the press announcement of the Aliquippa slabbing mill by Westinghouse says, 'If we hurry we might at least be the first to put it on the hot strip mill.'[6]

Pioneer computer use in UK

As early as 1953, the Ferranti computer at Manchester University was used by the British Iron and Steel Research Association for statistical analysis of blast furnace behaviour.[7] In 1957 the British Iron and Steel Research Association (BISRA) issued a detailed 24 page publicity booklet *Computers and Steel* to steelmakers to explain how computers work in simple terms (Fig. 1).[8] This promoted the new BISRA Computer Applications Section, set up within the Association's Operational Research Department, and reported that BISRA had decided to buy a Ferranti Pegasus computer which was delivered in 1957. The main focus of the booklet was on payroll applications pioneered elsewhere in the UK, at Lyons Bakeries.[9] At the time, the price of a Ferranti Pegasus 1 suitable for operations research purposes was quoted to the Steel Company of Wales at £49 450 in July 1959.[10]

Among the first business computers in world steel was the Leo II started at Stewarts & Lloyds Ltd, Corby in June 1958.[11] This was the first Leo II computer to be installed outside Lyons. Its main function was payroll calculations, but it was also used for stress calculations on tubes and operations research applications in iron ore mining.[12] It ran until 1971.

By 1958, there were a dozen different types of computer available in the UK, more than in the USA and Europe.[13] At that stage, business applications predominated, accounting for 47 of the 125 computers installed in the UK (Table 1). Typical industrial applications included the statistical analysis of sales and the allocation of can production across factories using linear programming at Metal Box;[15] the statistical analysis of Customs and Excise import data for the Cotton Board on a Ferranti Pegasus at Imperial Chemical Industries (ICI) Dyestuffs, Harpurhey, Manchester;[16] and recording prices for paints at ICI using an IBM 650.[17]

First process control computers in steel

The iron and steel industry was at the forefront of the application of computers for control purposes. The USA led the way, reflecting the dominance of the American steel industry in the 1960s and the availability of standard computers suitable for industrial application. Approximately two-thirds of installations listed in Table 2 were

Table 1 Early applications of UK built computers,* 1958

Use	Installed in UK	'Installed overseas'
Engineering design	32	3
Other mathematical work, research statistics and university mathematical laboratories	27	8
Service bureaux, testing of customer programs, etc.	19	…
Business applications: accounting, payrolls, stores records and management statistics	47	1
Total UK computers	125	12

*Source: Gearing,[14] Table 2.

Table 2 World stock of process control computers for steel applications,*† January 1964: total number 62

Firm, location	Use	Type of computer	Manufacturer
Power generation (total 4)			
Bethlehem Steel, Lackawanna, USA	Operating guidance	GE 312	General Electric
Italsider S.p.A., Taranto, Italy	Utilities dispatch	CEA 2801	Construzione Electro Meccaniche Annettoni (Italy)
Bethlehem Steel, Burns Harbor, USA	Operating guidance	H 610	Honeywell Inc.
Midwest Steel Corp., Portage, Indiana, USA	Plant demand	Bailey 756	Bailey Meter Co.
Burden preparation and coke ovens (total 2)			
Youngstown Sheet & Tube, East Chicago, Indiana, USA	Sinter data logging	GE 312	General Electric
S.A. Forges de la Providence, Belgium	Sinter log	ACEC 51	
Ironmaking (total 4)			
Inland Steel, Indiana Harbor, USA	Data logging	IBM 1710	IBM
United States Steel, Homestead, USA	Data logging	Fox 97600/PDP4	Foxboro/DEC
Hoogovens, IJmuiden, The Netherlands	Data logging	Elliott Arch	Elliott Automation
Nippon Kokan KK, Japan	Data logging	Hokushin	Hokushin Electric
Steelmaking: electric arc (total 5)			
Lukens Steel Co., Coatesville, USA	Power demand	IBM 1710	IBM
Steel, Peech & Tozer, Rotherham, UK	Load management	Argus 108	Ferranti
Armco, Kansas City, USA	Power demand	Bailey 760	Bailey Meter Co.
Interlake Steel, Ohio, USA	Power demand	Bailey 760	Bailey Meter Co.
Timken Roller Bearing Co., Ohio, USA	Power demand	Bailey 760	Bailey Meter Co.
Steelmaking: basic oxygen (total 13)			
Great Lakes Steel, Detroit, USA	Guidance	TRW 330	Bunker-Ramo
Bethlehem Steel, Lackawanna, USA	Control oxygen, lance	GE 412	General Electric
Sharon Steel, Farrell, USA	Control oxygen, lance	H 290	Honeywell
Ford Motor, Steel Division, Dearborn, USA		H 610	Honeywell
United States Steel, Duquesne, USA	Guidance	TRW 340	Bunker-Ramo
Fuji Iron and Steel, Japan		TRW 330	Bunker-Ramo
Nippon Kokan KK, Japan	Guidance	HOC-300E	Hokushin Electric
GKN, Lysaght's, Scunthorpe, UK	Guidance	KDN 2	English Electric
Usinor, Denain, France	Guidance	RW 300	Bunker-Ramo/CAE
Italsider S.p.A., Taranto, Italy	Guidance (charge calculation, data logging)	CAE 510	Comp. Européene d'Automatisme Electronique (France)
Italsider S.p.A., Bagnoli, Italy	Guidance	CAE 510	Comp. Européene d'Automatisme Electronique (France)
Armco, Ashland, USA	Guidance	IBM 1620	IBM
Jones & Laughlin, Cleveland, USA	Guidance	TRW 330	Bunker-Ramo
Reversing hot mills (total 10, one nickel)			
Lukens Steel Co., Coatesville, USA	Plate mill	GE Directomatic	General Electric
Armco, Kansas City, USA	Plate mill/slabbing mill	Prodac P 4449	Westinghouse
Crucible Steel, Midland, Pennsylvania, USA	Rougher to strip mill	Prodac P 4449	Westinghouse
Republic Steel, Gadsden, USA	Plate mill screwdown	Prodac P 4449	Westinghouse
Inland Steel, Indiana Harbor, USA	Bloom/billet mill	GEPAC 4000	General Electric
United States Steel, Gary, USA	Plate mill scheduling	Prodac P 4449	Westinghouse
Italsider S.p.A., Taranto, Italy	Slab mill scheduling	IBM 1460	IBM
Italsider S.p.A., Taranto, Italy	Plate mill control	Prodac P 500	Westinghouse
Armco Steel, Middletown, USA	Blooming mill	IBM 1710	IBM
Inco	Combination mill	IBM 1710	IBM
Hot strip mills (total 10, one aluminium)			
Great Lakes Steel, Detroit, USA	Control	Daystrom 136	Control Data
McLouth Steel Corp., Trenton, USA	Control setup finishing	GE 312	General Electric
Inland Steel, Indiana Harbor, USA	Control	Prodac 580	Westinghouse
Wheeling Steel Corp.,	Control	Prodac 500	Westinghouse
RTB, Spencer Works, Llanwern, Wales	Control	GE 412	General Electric
Hoesch AG, Dortmund, Germany	Scheduling	GE 412	General Electric
Steel Company of Wales, Port Talbot, Wales	Control	GE 412A	General Electric
Bochumer Verein, Germany	Scheduling	GE 412	General Electric
Bochumer Verein, Germany	Control	GE 412	General Electric
Alcoa, Warwick, Indiana, USA	Control	Prodac 580	Westinghouse
Cold strip mills (total 6)			
United States Steel, Fairfield, USA	6 stand control	GE 412	General Electric
Steel Company of Wales, Port Talbot, Wales	4 stand control	TRW 330	Bunker-Ramo
Inland Steel, Indiana Harbor, USA	3 stand data logging	GE 312	General Electric
Atlas Steel, Welland, Ontario, Canada	Z mill	IBM 1710	IBM
Mannesmann AG, Germany	Sheduling	GE 412	General Electric
United States Steel, Gary, USA	6 stand control	Prodac 580	Westinghouse
Processing lines and long product rolling mills (total 8)			
Inland Steel, Indiana Harbor, USA	Galvanising line	IBM 1710	IBM
Jones & Laughlin, Aliquippa, USA	Tinning line	RCA 110	Radio Corp. of America
Jones & Laughlin, Aliquippa, USA	Tinning line	GE 412	General Electric

Table 2 World stock of process control computers for steel applications,*† January 1964: total number 62 (continued)

Firm, location	Use	Type of computer	Manufacturer
Jones & Laughlin, Aliquippa, USA	Annealing line control	GE 312	General Electric
Kaiser Steel, Fontana, USA	Tinning line	GE 312	General Electric
United States Steel, Pittsburgh, PA, USA	Tinning line	GE 412	General Electric
Samuel Fox, Stocksbridge, UK	Billet cutting	Elliott 803	Elliott Automation
Shelton Iron & Steel, Stoke, UK	Beam cutting	KDN 2	English Electric

*Sources: developed from Kirkland,[18] p.116; *Control Engineering*,[19] pp.78–79; *Journal of Metals*.[20]
†Possible omissions include one Swedish process control computer, one French research computer and Italsider, Piombino research computer. Please point out other omissions. Status 1964. Some locations had already upgraded from earlier machines. Excludes hard wired card control.

located in the USA. Steelmakers employed second generation computers which used transistors as a basis for reliable mainframe computing. They exploited magnetic core memory storage invented by Forrester in 1950. (Pioneering British computers relied upon cumbersome delay lines – precisely machined mercury filled tubes – for data storage.)

The journal *Control Engineering* published a sequence of surveys on process computer use at 18 monthly intervals in the 1960s, listing every digital process control computer in the world (Tables 3 and 4). There are gaps in their lists owing to the omission of a few International Business Machines (IBM) computers installed outside the USA,[25] but the company was not the major player it became in the late 1960s – far from it. These surveys show that four industrial sectors dominated early industrial computer use: power generation; petroleum and chemicals; metals, effectively steel; and a set of miscellaneous high technology engineering sectors.[26] The USA led in industrial application of computers with almost 400 by 1965, compared with 54 in the UK, 39 in France, 13 in Italy and 12 in Japan. Of the world total, 100 were involved in iron- and steelmaking, or 18% of the total market for control computers.

General Electric (GE) were the leading computer suppliers to steel. By 1965, GE had 25% of the world market for process control computers in metals, followed by Westinghouse with 17%. Bunker-Ramo was pre-eminent across all sectors in process control with over 100 installations worldwide by 1965, half of them in petroleum and chemicals, yet supplied less than 10% of process computers in the metals sector.

The UK steel industry was also a leader in the application of computer control to steelmaking, despite the small size, fragmented nature and scientific bias of the British computer industry;[25] UK steel accounts for seven of the 60 or so early steel industry computers listed in Table 2. The publicly owned Italian steelmaker, Italsider, played a pioneering role using Italian, French and American computers.[20] In terms of companies, Jones & Laughlin and Inland of the USA, the Steel Company of Wales and Italsider were among the leading innovators, judging by the listings in Table 2.

The Japanese steel industry adopted computers later, with early installations confined to three advisory systems for blast furnaces and oxygen steelmaking. For some reason, France stood on the sidelines, with just one basic oxygen steelmaking (BOS) shop installation at Usinor by 1965 using American knowhow from Bunker-Ramo,[27] although the Institut Recherche Siderurgie (IRSID) was active in experimental research.[28] As late as 1969, the collaborative research institute Centre National de Recherche Métallurgique (CNRM) in Belgium also presented an explicitly negative view of automation in steel.[29]

Evidently, adoption of computer control for the steel plant was not a forgone conclusion even by the end of the 1960s. Marked differences between Italian and French adoption rates are striking. Both steel industries pursued state sponsored expansion schemes characterised by heavy investment in new steelworks.

Table 3 Number of process control computers, all applications,* 1963–67

	USA	UK	France	West Germany	Italy	Japan	World total
Sept. 1963	237	34	27	4	4	9	340
March 1965	396	54	39	9	13	12	565
Sept. 1966	761	129	95	22	14	71	1325
March 1967	866	132	122	58	<20	99	1571

*Sources: *Control Engineering*.[19,21–23]

Table 4 Number of process control computers by industry,*† 1963–68

	Petroleum, chemical, paper, food, cement	Metals (almost all steel)	Power	Miscellaneous (e.g. astronomy, nuclear, space)	World total
Sept. 1963	92	55	117	76	340
March 1965	166	106	161	132	565
Sept. 1966	336	242	289	485	1325
July 1968	>632	397	504	781	2890

*Sources: *Control Engineering*.[19,21,22,24]
†Last survey date excludes minicomputers, but has wider coverage in miscellaneous category. No separate data available for food industry in 1968.

Contrasting experience across countries shows that adoption of computer control was not an automatic consequence of capital investment during the 1960s. Rather, it required a conscious decision to develop computer control in place of manual operation. Management enthusiasm for computer control helps to explain why UK steel rapidly adopted computerisation at a time when the industry was otherwise slow to take up process innovations such as oxygen steelmaking and continuous casting.[30]

Supervisory role of early computers

Early computers were limited to an advisory role. Among the first applications of a computer to any iron- and steelmaking process was the use of a GE 312 computer for data logging on the sinter plant of the Youngstown Sheet and Tube Co. at Indiana Harbor in 1959.[31] The system was handicapped by the problem of obtaining representative samples for analysis – an early example of the recurring problem of gaining accurate and reliable signals from sensors. The preprogrammed GE 312 GARDE system sold by General Electric was explicitly designed not to implement control actions. Its supervisory role is emphasised by the GARDE acronym: 'Gathers Alarms Records Displays Evaluates'. Control was left to human operators.

In general, sensing devices were not reliable enough to allow direct online process control at the ironmaking and steelmaking stage. Ambitious early attempts at blast furnace control in The Netherlands concluded that development of better measurement instruments was crucial.[32] A GE representative discussing the possibility of online control of blast furnaces said bluntly at the time, 'measurements of internal conditions within the furnace are not yet satisfactory.'[33]

First online computer control: McLouth at Trenton

Online computer control of steelmaking processes became a reality with the first use of computers on a hot strip mill in 1962. McLouth, at Trenton, Michigan used a GE 312 computer for gauge control on the finishing train of a semicontinuous mill. The aim was to set up the initial roll gap and then establish correct gauge as soon as the head end of the strip emerged onto the runout table.[34,35] The finishing train started running under continuous computer control on 1 November 1962. H. Oldfield, General Manager of the GE Computer Department, recalls:[36]

'Probably the most exciting application of the GE 312 was to the hot strip mill of McLouth Steel Co. in Michigan. It was a difficult design inasmuch as each step in the process had to be varied on the basis of the measured values of the previous step. This required continuous high speed feedback to set the five different hot stands with absolute accuracy and reliability being essential; an error at one point could be magnified at the next, causing the entire process to go out of control. Fortunately, the GE 312 met the challenge.'

Hence, direct digital control of wide strip mills became the first successful full scale application of computer control in steel production.

The solid state circuitry of a GE 312 computer was composed of 2500 diodes, 2500 transistors and 12 000 resistors, but no magnetic core memory. There were 20 binary digits (bits) per word or per instruction. All arithmetic was fixed point. Numbers were 19 bits plus the associated positive or negative sign, not a very big number range when expressed in decimal form, just $-524\,287$ to $+524\,287$.[37] The GE 312 was designed by A. Spielberg of the GE Computer Department newly formed in 1957.[38] He had been recruited from Radio Corp. of America (RCA) to head the Process Control Engineering section of GE.[39]

Llanwern hot strip mill: pioneering installation

The first successful use of a computer for complete mill control was the new generation II hot strip mill at Richard Thomas and Baldwin's Spencer steelworks, Llanwern, near Newport in Wales, which introduced direct digital control of the whole mill in 1964.[35,40,41] The main functions of the process control computer were initial setup, active operation and adjustment during rolling, sequence control of slabs and coils through the mill and logging of production. The computer was also meant to optimise mill performance, but here it was less successful.

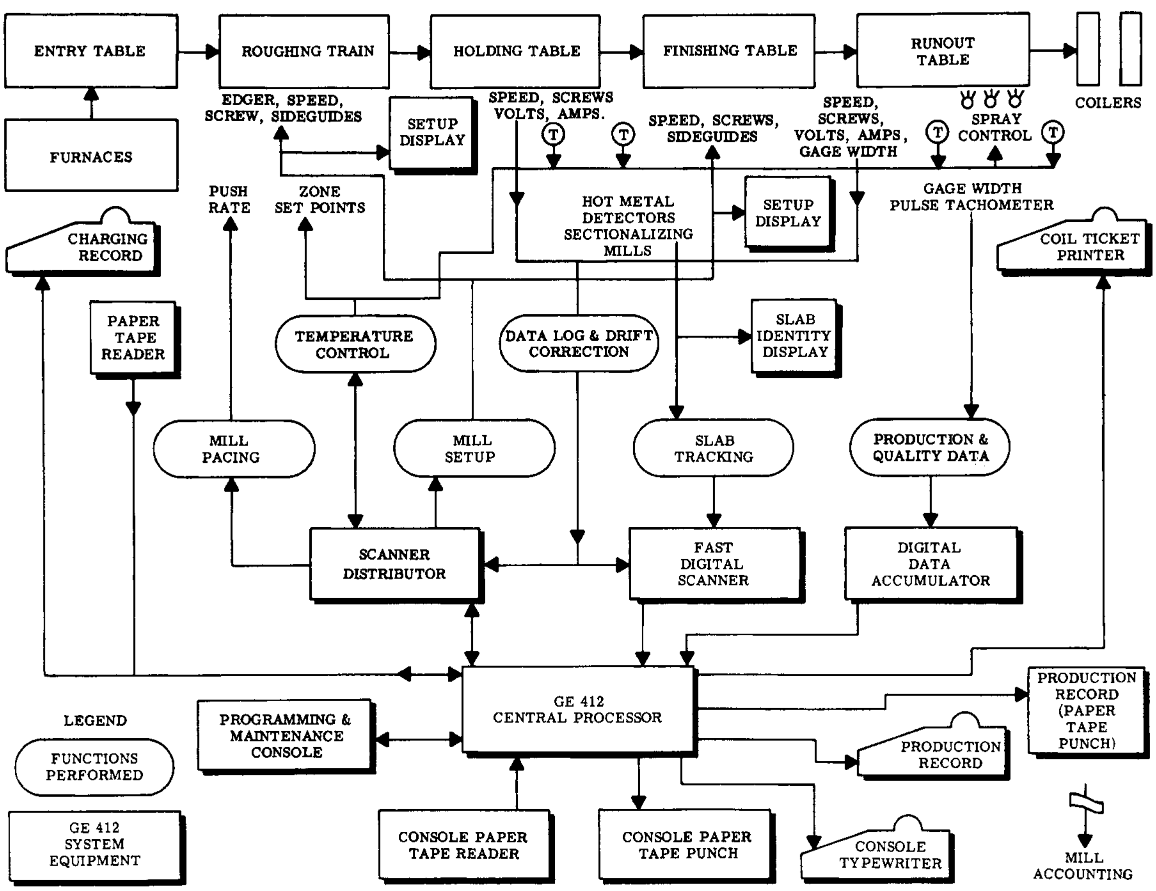
The installation at Llanwern used an American built GE 412 digital computer to control the whole mill (Figs. 2 and 3). The GE 412 was essentially the earlier GE 312 computer with a core memory added.[42] The 412 was specifically designed for process logging, monitoring and control in applications such as electric power plants and manufacturing.[43] Computer makers in the USA were far more focused on commercial and industrial applications at the time, and helped by a large domestic market for industrial equipment.

The Llanwern computer was installed in a room alongside the mill pulpit in air conditioned cabinets. It was a stored program computer with an 8192 word high speed magnetic core storage and a 57 344 word magnetic drum 'bulk storage' backup. Again, it had solid state circuitry. The limiting factor was the design and cost of memory. In common with early computers, it had a magnetic core memory based on thousands of doughnut shaped ferrite cores.[44] It is a tribute to the software programmers that a complete hot strip mill could be run on a computer with processing power equivalent to a modern pocket calculator.

The use of core memory at Llanwern seems to have been crucial. The first practical attempt at computerised setup of a tandem mill in the UK was at Port Talbot in 1962 on their four stand cold mill, with the installation of a TRW 330 computer which had a 28 bit word length and a 48k drum, but no core store, the equivalent of random access memory (RAM) on modern computers.[45] Thus, all computations had to rely on reading the programs from a drum and then carrying out the necessary manipulations of the data on the drum also. Much thought was given to trying to optimise the location of programs and data on the drum to minimise the latency time while waiting for the drum to rotate. As a result, there were numerous commissioning difficulties.

Similar problems dogged the first use of computers on a process line. Jones & Laughlin installed a computer on

2 General Electric (GE) 412 computer was mainstay of hot and cold strip mill computer control worldwide during early 1960s: courtesy K. Morgan



3 GE 412 computer that ran whole of Llanwern hot strip mill from 1964 relied on careful programming to overcome low computer power: courtesy K. Morgan

their Aliquippa works continuous annealing line in 1960. This was a GE 312. Its functions were material tracking, process monitoring, process control and production reporting. Progress in control was hampered by an inadequately sized memory drum and closed loop control was not achieved until 1963.[46]

Hence, a key breakthrough at the Llanwern hot strip mill was the ability to respond to signals immediately using core memory. The man responsible for adding the core memory to the GE 412 was Spielberg, prior to his departure for IBM in September 1963. (He has since become more famous for coaching his son in the art of making home movies.[39])

The aims of the Llanwern computer were:

(i) to express rolling relationships mathematically
(ii) to set up the mill using computer signals
(iii) to track slabs as they progressed through the mill
(iv) to respond to sensors while the mill was rolling
(v) to give output corrections to actuators
(vi) to log production.

Computer control at Llanwern was comprehensive: It not only controlled mill setup and operation on the roughing and finishing train, but it also controlled the reheat furnaces and coiler (Fig. 3). Sensors tracked the position of material as it flowed through the mill, and measured speed, gauge, width and temperature. In response, roll gaps, edger positions and side guides, mill speed and cooling sprays were controlled. Recall too, generation II mills were designed for zoom rolling whereby the strip was progressively accelerated as it passed through the finishing train once the head end had been threaded onto the coiler. All in all, the computer received 200 analog and 75 digital signals and maintained 300 output contacts and 150 other various digital outputs.

Commissioning took place in stages. The computer started running in February 1963. The automatic crop shear started in July 1963 and gauge control in October 1963. But it took another year before slab tracking, logging and all the mill setups and temperature controls were fully operational, by October 1964.

Computer hardware proved surprisingly reliable. During the first 18 months of operation the computer was available for more than 99·9% of operating time. Instead, it was the conventional electromechanical features of the mill that caused problems, along with shortcomings in the pioneering software.

Computer developments in South Wales

The Llanwern installation was replicated at Port Talbot using a GE 412A.[47] Full computer control commenced there in September 1966, apart from mill pacing.[48] The only key difference between the two installations was that Llanwern tracked the slabs through the reheat furnaces, whereas computer control at Port Talbot began with the roughing train. A participant of the time, K. Morgan,[49] recorded his experiences developing 'hands free' computer control at Port Talbot. The system operated using GE 412-PAL – the General Electric 'program application language'. Data for the rolling schedule for a complete shift was input on punched cards. The same team of computer personnel then progressed to the new tinplate works of the Steel Company of Wales at Trostre.

Contract details of these early computers have not been traced. It is known that General Electric sold its simpler 312 GARDE system for $US275 000 at the time, plus $US25 000 for the basic peripherals.[50] General Electric also sold 8192 word location memories for $62 400 in 1964. Hence, it is reasonable to suppose that the GE 412 computer for Llanwern cost Richard Thomas and Baldwins in excess of $US400 000 after paying import duty – some £143 000 at the ruling exchange rates. Cartwright[51] gives a budget of £2·4m for the whole Port Talbot scheme, but two-thirds of this was allocated for upgrading the mill with a new edger, loopers, screwdowns and drive control on the hot strip mill to improve control.

South Wales had one of the densest concentrations of computer control in world steel by the end of the 1960s. This was no accident. The cluster of computer applications owes its success to two factors. First, there was an interchange of expertise and personnel. Knowledge of process control techniques and programming skills spread rapidly in this environment as key personnel moved from job to job. As another veteran, A. Foss,[52] expressed it, 'In those days few people knew about computers and everyone was self-taught.' Hence, networks of likeminded people helped diffusion of the new technology.

Second, senior management were champions of computerisation. The Chief Executive of the Steel Company of Wales, F. W. Cartwright, took a personal interest in computers. He chaired internal meetings promoting computer use. Taking one well documented instance, the Steel Company of Wales (SCOW) held an internal afternoon conference on electronic digital computers on 10 March 1959 for senior staff, chaired by Cartwright.[53] The participants watched films on Leo and Pegasus computers and heard four short talks on equipment, construction, programming and the economics of computer application followed by questions to an expert panel. This was a typical event, led by the directors, to spread knowledge of computers through the company. Someone with specific responsibility for automation gave regular monthly reports to the SCOW board. Cartwright himself gave the fourth annual lecture of the UK Automation Council in 1964.[51]

South Wales spawned a further breakthrough in computer control. In 1966, a consortium was established to develop a rolling mill model involving the Ministry of Technology, the electrical company Associated Electrical Industries (AEI), Imperial College and the Steel Company of Wales. A successful model was developed between 1968 and 1971 and applied to the revamped cold tandem mill at Port Talbot works.[54] The model was then used at the new Shotton five stand tandem mill in North Wales, and eventually on almost every hot and cold strip mill in the British Steel Corp.[55] The team included Professor G. Bryant and J. Edwards at Imperial College and D. Harvey, K. Edwards and R. Griffiths at the Steel Company of Wales. A former joint chief executive of Corus observes that this initiative was 'quite a remarkable exercise in transforming the automation of rolling mills – not just in the UK but worldwide'.[56]

Shortcomings of early computers

Computer control worked well in the UK. The GE 412 computer was a very successful system which performed as planned, apart from the mill pacing function which did not work. Mill pacing was meant to maximise throughput without damaging either the mill equipment or the strip itself. The failure of mill pacing led to hardware reconfiguration and local development of software to improve mill output, reducing delay time between successive bars, for example. These problems were common to Llanwern and Port Talbot. However, otherwise, strip mill control was highly successful in Britain. By the end of 1969, five systems were installed on UK hot strip mills (Llanwern; Port Talbot; Ravenscraig; Lackenby coil plate mill for gauge control; and Brinsworth narrow hot strip mill).

Computer control of hot strip mills was not such an unequivocal success in the USA. A key American survey was highly critical of the limited results achieved after the first 5 years of computer operation of hot strip mills.[57] There were a total of 10 attempts to introduce direct digital control on new generation II hot strip mills in the USA, but in contrast with the UK these enjoyed only mixed success.[58] In particular, there were failures in the area of furnace heating control, mill pacing and coiler control (e.g. Ref. 59). There was no evident reduction in overall mill manpower, while maintenance technicians and software programmers were specifically required for the computer. Similarly, Coheur[29] reports an American study which found that only 12% of US steel companies questioned in 1965 were able to assess the profitability of their investment in either administrative or process control computers. Yet a detailed report on a very early installation for computer control of billet cutting on a rolling mill at Stocksbridge in the UK showed annual savings from yield gains to outweigh the total initial cost of the scheme, implying a very rapid payback on the initial investment in equipment and programming.[60]

Nevertheless, by the end of the 1960s some 24 computers were in use or being installed on hot strip mills worldwide, including five in the UK and 10 of the 11 new second generation mills built in the USA.[35] Progress was helped by reliable and accurate instrumentation available for hot strip mills, notably for thickness, width and temperature.

Order handling and scheduling

Computing progressed at an extraordinary speed during the 1960s. The IBM 360 series of mainframes was launched in 1965 and quickly became the standard in international computing. Key features included software that was compatible across computers; a wide range of sizes and power across the whole 360 series; and suitability for both business and technical use, by allowing short and long word applications.[61] Moreover, IBM were supported by their technical leadership in magnetic disk drives developed at their San Jose research laboratories between 1952 and 1956.[62]

The steel industry was quick to spot the potential of larger computers for production planning. John Summers and Sons commissioned an IBM 360, model 30 with six disk drives at Shotton on 3 April 1967 for order handling and production control (Fig. 4).[63] At the outset, orders for strip and coated coil were accepted on the computer and process routings identified. The aim was to schedule orders through the various production stages and produce the necessary documentation. A purpose built, steel clad computer centre was erected to house the computer in an air conditioned 'clean room' environment as well as its 50 associated staff.

4 IBM 360 series was widely used for management tasks by late 1960s: this IBM 360 was installed in a purpose built steel building at John Summers and Sons, Shotton Works: courtesy Corus Colors

Production control and scheduling was a priority also in Japan. The complexity and size of process flows at the Yawata-Tobata works made production planning imperative.[64] The software was based on backward induction, a variant of the familiar 'travelling salesman' problem once taught to Fortran programmers. To solve the problem, it is necessary to start at the destination and work backwards to identify the ideal departure time from the origin. In the same way, the loading operation at Yawata-Tobata for monthly, weekly and daily schedules simply reversed the product flow. Starting with anticipated orders on the rolling mill, the computer worked backwards to calculate the implied flow through the preceding primary mills, and then allocated output schedules to the steel plants, including two BOS shops, an arc melting shop and a range of open hearth furnaces. A similar installation using a HITAC 4010 computer (an RCA 3301 made under licence by Hitachi) was installed at Hirohata works in 1965.[65]

Furnace control in Rotherham

Process control computers were widely used in the electricity generating sector itself, so major consumers of electricity were quick to appreciate their cost saving potential. Steel, Peech & Tozer's Templeborough plant was one of the largest electric arc melting shops in the world in the early 1960s, and hence they had much to gain from computer control of power usage.

The Central Electricity Generating Board provided power to Templeborough under a bulk supply agreement which imposed local limits on consumption, with costly penalties if these limits were exceeded at times of peak demand on the overall electricity supply network. A Ferranti Argus 108 was installed to control power supply to the six furnaces in the melt shop.[66] This was able to monitor and predict electricity use and cutoff or reduce the offtake of power at peak times in a way that optimised furnace use. For instance, the first furnace to be restricted would be the one that had most recently commenced melting, since the rate of potential heat loss from stoppage increases with the progress of the melt, while loss of power during refining may adversely affect metallurgical conditions. A very similar system was developed 10 years later in Krefield.[67]

Billet optimisation at Parkgate Iron and Steel

Parkgate Iron and Steel at Rotherham developed two innovative schemes for early rolling mill control during 1963 and 1964. One scheme used an English Electric KDN2 computer to optimise and control the cut to length shear on a bloom billet mill. Foss[52] described the KDN/KDF machines as 'good fast processors with mnemonic code software that was easy to understand and implement.' This was online real time control using a computer with 4k core memory based on germanium transistors, 'which was more than adequate for control of major items of plant', according to Foss. There was also an English Electric KDF6 mill pacing computer. This had an innovative alphanumeric display driven by a Marconi character generator. A digital memory based control system also controlled the pass sequences for a reversing blooming mill. Finally, there was a KDF6 computer used for order processing using conventional data cards.

Diffusion of process control computers

By 1969 there were over 3000 computers used in various industrial processes throughout the world (of a total world stock of computers then approaching 100 000). Of these, some 400 computers were associated with iron- and steelmaking worldwide. Among them, approximately 50 were in the UK by 1969 and around 80 by the beginning of 1970.[35]

In 1970, the recently formed British Steel Corp. (BSC) published a list of their industrial computers in operation or awaiting delivery for a parliamentary enquiry (Table 5),[68] although there are omissions from the list such as the Leo II at Corby. At the time, BSC operated $\sim 1{\cdot}5\%$ of the UK computer stock.[69] The Corporation had at least 48 business computers and 36 process control computers, although the distinction is not clear cut. At least six of the business computers were associated with technical R&D, operations research or statistical analysis. The number of business computers was then declining, as BSC rationalised its operations around fewer, but more powerful, machines such as IBM 360/40s and 50s linked by telephone lines. By 1970, computers had been in use in the steel industry for a decade, and there was scope for rationalisation across the newly formed Corporation.

A breakdown of process computer use in BSC in Table 5 highlights the following points.

1. Some process areas were completely devoid of computer control in the UK. There were no applications to burden preparation which was among the first applications to be debated in the USA, USSR[70] and France. The new technology of continuous casting was not computer assisted.

2. Second, only one works – Port Talbot – had computer control at all stages in the production process. The former Steel Company of Wales was all the more impressive as a pioneer given their role at Trostre and Velindre and their initial work on cold mill control.[18] The only comparable plants in terms of breadth of computer applications were Italsider at Taranto, or Inland Steel in the USA.

3. Third, process computers were clustered geographically in South Wales, South Yorkshire and the former Colvilles works in Scotland.

4. Fourth, strip mill applications dominated in terms of both number and complexity over long products. Then, as now, section mills were a 'black art' far removed from computer control.

5. The size, sophistication and extent of computer control varied from minor task to comprehensive control. For instance, the Digital Equipment Corp. PDP 8 series computer at Bilston was a no frills, low end, cheap computer performing a very simple operation. The PDP 8 was the first commercially successful minicomputer and sold for one-fifth of the price of a basic IBM 360: only $18 000 in the USA. Hence, it was ideal for a simple process control task such as cutting bars to length. It was also small – tabletop size – and had a video display terminal.

6. There was an extremely wide variety of computers in use, partly due to the fragmented nature of the UK computer industry at that time. Each computer required specific software which was incompatible with other machines. There was some degree of standardisation, such as the use of Elliott Arch machines in South Wales. Indeed, by 1968 the merged English Electric and Elliott Automation became the second largest supplier of process control computers in the world ahead of IBM.[71] The Ferranti Argus series was coming into widespread use. Otherwise there was very little hardware or software compatibility across the industry at the time. However, in its day, the GE 412 was something of a world standard for strip mills, with applications in South Wales, Bochum, Dortmund and Duisburg, as well as process lines and cold mills in the USA. (The GE 412 was known as the AEG GEAMATIC 1005 in Germany.) However, both Ferranti and GE were to leave commercial computers, so even this degree of standardisation was not to persist.[72,73]

7. Finally, in some areas of technical leadership, such as strip mill control, computer use diffused rapidly across plants, firms and countries helped by the marketing prowess of GE Computers. Yet the pioneering work on electric arc furnace load control at Steel, Peech & Tozer was confined to just one location in the UK and not replicated for another 10 years.

Retrofitting

By 1970, computer control had become an accepted feature of rolling mill operation, though they were often limited to specific tasks such as setup and gauge control. For example, a Ferranti Argus 500 was fitted to the Brinsworth narrow strip mill finishing train between 1970 and 1972. This had a 32k core memory (four times the size of Llanwern), used a 24 bit word length and a hard disk memory store of 0·6 m in diameter. Paper tapes were used as the storage media for instructions. The finishing mill setup was derived from physical model calculations and temperature measurements. In all, 91 devices were controlled, including the setting of roll gaps and motor speeds across six stands, plus looper pressures and coiler settings. An important feature was a secure software structure to avoid crashes. The Ferranti Argus was powerful, flexible and easy to use, but it was considered too expensive for general use.[52] A General Electric Co. (GEC)/AEI Con Pac 4060 was retrofitted on the Lackenby universal plate mill stand and on the finishing train of the coil plate mill. The use of computers began to diffuse rapidly, especially as steelmakers appreciated their 'retrofit' capabilities to tweak the performance of existing aging facilities.

Computers were also used for reheat furnace control where they were first employed by the British Steel Corp. in 1977.[74,75] Furnace set points were selected from a 'carpet diagram' relating temperature to the type of slabs and throughput rate. The background diagram

Table 5 Use of process control computers in British Steel Corp.: status at 1 January 1970, installed or awaiting delivery*

Function	Type of computer	Location	Serial no.
Burden preparation and coke ovens			
(None)			
Ironmaking			
Control of blast furnace	Ferranti Argus 500	Port Talbot	12
Control of combustion in stoves	Hawker Siddeley DCC2	Redbourn	13
Steelmaking			
Electric arc			
Control of power input	Ferranti Argus 100	Templeborough, Rotherham	1
Basic oxygen			
Data logging and control of steelplant	English Electric KDN2	Normanby Park	4
Control of steel plant	English Electric/Marconi Myriad II with touch screens	Port Talbot	14
Control of steelmaking	English Electric KDN2	Ravenscraig	30
Open hearth			
(None)			
Bessemer			
Control of furnace	Ferranti Argus 350	Workington	2
Chemical analysis			
Steel analysis from Quantovac output	English Electric KDN2	Sheffield	3
Continuous casting			
(None)			
Rolling mills			
Slabbing and blooming mills			
Control of cutup at shears	English Electric KDN2	Rotherham	10
Control of rolling rate	English Electric KDN2	Rotherham	11
Control of soaking pits	Ferranti Argus 108	Redbourn	15
Control of soaking pits	IBM 1800	Bilston	26
Control of soaking pits	English Electric KDF7	Ravenscraig	31
Control of slabbing mill	English Electric M2140	Ravenscraig	32
Hot strip mills			
Control of hot strip mill	General Electric 412	Llanwern	16
Control of hot strip mill	General Electric 412A	Port Talbot	17
Mill setup and control	Ferranti Argus 500	Brinsworth	6
Slab pacing from reheat furnace to coilers	Ferranti Argus 104	Brinsworth	7
Gauge control on coil plate mill finishing train	GEC/AEI Con Pac 4060	Lackenby	28
Control of hot strip mill	English Electric M2140	Ravenscraig	33
Cold strip mills			
Control of 5 stand tandem mill (converted from 4 stand, *see* Table 2)	GEC/AEI Con Pac 4060	Port Talbot	18
Data logging on reversing mill	Ferranti Argus 400	Newport	19
Data logging on 3 stand mill	GEC/AEI Con Pac 4060	Trostre	20
Data logging on 5 stand mill	Elliott Arch 1000	Velindre	21
Plate mills			
Gauge control on universal plate mill stand	GEC/AEI Con Pac 4060	Lackenby	27
Control of reversing plate mill	English Electric M2140	Dalzell	34
Section mills			
Section cutup and tracking	Ferranti Argus 500	Scunthorpe	9
Control of saws on section mill	English Electric KDN2	Shelton	35
Control of section mill	English Electric M2140	Colvilles	36
Billet, bar and rod mills			
Data logging and information display	Elliott Arch 1000	Stocksbridge	5
Control of billet cutting to length	Elliott 803A	Stocksbridge	8
Control of hot bar cutting	Digital Equipment PDP 8/S	Bilston	29
Process lines			
Control of electrolytic tinplate line	Elliott Arch 9000	Ebbw Vale	22
Quality recording on tinplate line	Elliott Arch 1000	Velindre	23
Quality recording on tinplate line	Elliott Arch 1000	Trostre	24
Quality recording on tinplate line	Elliott Arch 1000	Trostre	25

*Source: derived from 'Computer policy',[68] Appendix B.

was based on extensive data logging of actual furnace behaviour. The computer simulated these initial set points and then modified them in the light of events, including the actual measured state of the reheat furnace, progress on the rolling mill and any unanticipated delays. The system was initially installed on two slab reheating furnaces of 180 and 220 t h^{-1} capacity at Lackenby, and brought fuel savings averaging 15%/week. Ultimately, two GEC 4080 computers were used to run the system.

New plant automation

By the 1970s new plant was designed for computer control from the outset (e.g. Ref. 76). In Finland, the number two plate mill at Rautaruukki Oy, Raahe was the first in the world to use hydraulic gauge control. This was controlled by an Interdata 7/16 computer with 16k of memory installed in 1976, which calculated and set up the pass schedules and operated the hydraulic gauge control during each pass online in real time.[52] The computer had to set the roll gap, count passes, carry out mill reversal and determine width and thickness of the plate through a schedule of 7–17 successive passes. The computer used a magnetic core memory without any backup hard disk. Hydraulic gauge control has a particularly fast response (10 ms) compared with conventional mechanical screwdowns. Again, the computer needed secure software to avoid catastrophic problems under load (with a rolling force up to 5000 t). Here too the approach was to look up stored tables of schedules for either straight through or broadside passes as appropriate. In principle, calculation of rolling equations provided a neater solution, but stored data had the pragmatic advantage of accuracy.

Interdata computers with 16k memory came to be widely used for flatness control systems in steel and aluminium from 1977 onwards, starting with the shape control system at the SIDAL in Belgium. These had the modern feature of a visual flatness display with a refresh rate of 50 ms. Shape control systems became widely applied on cold strip mills for aluminium and steel during the 1980s. The system controlled roll bending and cooling sprays on the basis of signals from a flatness measurement roll. This not only brought flatter strip, but more stable operation allowed faster rolling speeds. The main system was developed by Davy, but a rival system was later developed by Asea. Now shape control is a conventional feature of all mill control systems.

In due course, shape control became integrated with hydraulic gauge control on cold mills, but this required more powerful computers such as the PDP 11 series of computers. By 1991, direct digital control of individual hydraulic capsules was implemented at Iscor in South Africa using VME Motorola equipment. The operating system on the computer was set up to achieve 1 ms response times.

Move to distributed computing

Dividing computer programs into a sequence of subroutines became commonplace among software programmers during the 1970s. It was logical to suppose that computer hardware could be similarly distributed across individual tasks to provide local control of particular processes under the supervision of a central computer at the top of the hierarchy. As the price of hardware fell, minicomputers or programmable logic controllers (PLCs) became feasible for localised control of processes. These could be bolted on in an almost *ad hoc* way leading to quick upgrades and the progressive spread of computerisation across an increasing range of process control tasks. The third automation system of the Port Talbot five stand cold mill was undertaken using one online computer, a standby computer and various GEM 80 microprocessors.[55] The difficulty was that PLCs were becoming more powerful and widely used, but still did not achieve the very fast response times required for process control operations. Moreover, links between them were slow.

Process control at heavy end

Ironmaking and steelmaking themselves lagged behind in terms of process control, partly owing to sensor problems and partly because comprehensive thermochemical models do not always characterise the complex aspects of furnace operation very well. In steelmaking, early computers were limited to offering advice on charge weights and blowing times, given targets for end carbon and tapping temperature. For example, NKK used a Hokushin Electric computer to advise the operators of two 42 t BOS vessels. This used results from model calculations from one heat as the starting point for initiating calculations for the next.[77] A similar exercise on Kaldo converters at Sharon Steel was unable to achieve dynamic control, despite the slow pace of refining in the revolving vessels.[78]

Blast furnaces represented an even more complex modelling problem, but the payoffs in terms of energy efficiency were substantial. There were isolated pioneers such as NKK Kure.[79] Computer based artificial intelligence models for blast furnace control were developed simultaneously in Finland and the UK and marketed widely.

Integration of process control and quality: Linz hot strip mill

By 1990, the operations of scheduling, process control and data logging by computer had become universal, at least on flat product rolling mills and finishing lines.

During the 1990s large scale computer models were developed which allowed integration of scheduling and process control with quality assessment. This requires a real time model of metallurgical transformation during the rolling process. Developments by Voest-Alpine Stahl and VAI at Linz allow immediate predictions of quality for the whole length of a rolled coil. Luger and Hubmer[80] reported experience with the VAI-Q system at the Linz strip mill.[81,82] This is one of the oldest surviving hot strip mills in Europe, yet it makes a range of demanding products to high standards and sells profitably to sophisticated customers, especially for automotive applications. At four million tonnes a year, the Linz mill has a formidable output level for a semicontinuous mill of this design.

The starting point at Linz is a physical–metallurgical model to predict strip quality in terms of tensile strength, yield strength and elongation. This modelling project began in November 1995. Once it was established that an offline model gave accurate predictions of the mechanical properties of hot rolled coil, the model was used to control actual setup and cooling on the finishing train from January 2000 onwards. Strip varies throughout its length. Therefore, the model tracks each segment of the strip so that microstructure can be predicted and modified during final rolling and cooling. Optimum rolling and coiling temperatures are crucial for high strength low alloy (HSLA) steels, for example.

There are substantial commercial advantages from being able to predict the quality of each coil straight away. The coil can be passed on for further processing immediately. The whole length of the coil is 'checked' by inference, whereas conventional measurement is restricted to samples from the head and tail ends, which may be untypical anyway. There are substantial savings in alloying costs as it is possible to optimise mechanical properties such as tensile strength, rather than relying on overkill with expensive manganese additions at the steelmaking stage just to make sure.

The aim of computer modelling in steel now is to develop 'through process models', first to predict the influence of one process stage on the next and then to optimise the whole sequence of processes from start to finish. Through process modelling of cold rolling and annealing has received less attention than hot rolling. Bodin *et al.*[83] discussed development of the 'toolbox' approach at Corus for through process modelling of cold rolling, annealing and temper rolling of low carbon steels. The aim is to predict the final mechanical properties of a finished cold rolled coil by combining models of cold rolling, furnace and temper rolling processes. Hence, the cold rolling stage is concerned with predicting deformation resistance using the Bergstrom model to determine dislocation density. Models at the annealing stage focus on recrystallisation, precipitation and grain growth. For example, calculating free nitrogen helps to predict recrystallisation in a continuous annealing line. As with hot strip mills, the task is to gather the data, calibrate a model and then use it to predict behaviour for out of sample steel grades.

Evidently computer modelling is a way to make new products, and achieve higher capacity utilisation and yield. Winkler *et al.*[84] reported an optimisation package for sequencing strip through continuously linked pickle lines and cold mills. Application in a US plant brought a 5% increase in annual throughput with more even pickling speeds and a smoother flow through edge trimmers. This is exactly the same pacing problem that computer pioneers found so difficult to solve on hot strip mills during the mid 1960s.

Ultimately, the aim is a business model which optimises a complete production programme subject to constraints of equipment, manufacturing times and transport. In this way it should be possible to evaluate costs and profitability of a wide range of production choices. This kind of comprehensive computer simulation and control is not likely to arrive before the end of the present decade. By then, computer applications in steel will have reached their 50th birthday. This achievement will unify the two distinct strands in computer development apparent since the earliest days, namely business applications and process control.

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