D.T.N. Williamson

Edinburgh's Pioneer of Hi-Fi Sound Reproduction and Flexible Manufacturing

Joe McGeough

D.T.N. Williamson: Edinburgh's Pioneer of Hi-Fi Sound Reproduction and Flexible Manufacturing

J.A. McGeough

SCHOOL OF ENGINEERING,

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About the Author

Joe McGeough is the Regius Professor Emeritus of Engineering, The University of Edinburgh and served as Head of its Department of Mechanical Engineering for 8 years.

He is a graduate of Glasgow (BSc, PhD) and Aberdeen Universities (DSc). He has had both industrial and academic experience, starting as a vacation engineering apprentice whilst an undergraduate, then as a postgraduate at International Research and Development Ltd. He had academic appointments at Leicester and Aberdeen Universities and research fellowships at Queensland and Strathclyde Universities.

His main field of research is electrochemical machining (ECM), an unconventional method of shaping hard alloys without tool wear, and recently of semiconductor materials. The Institution of Mechanical Engineers awarded him and his co-author the William Sweet Smith Prize for their paper on ECM drilling of small holes in aerospace alloys. This technology to which McGeough has contributed is used by an aircraft engine manufacturer to drill an estimated 1.9 million holes per year in gas turbine blades. A manufacturer of domestic shavers drew on McGeough's researches to micro-ECM shaver heads. About 20 million shavers are made per year. His work on ECM surface finishing of dies and moulds has been adopted by SMEs (small to medium-sized enterprises), through tenure of a Royal Society/Science & Engineering Research Council Industrial Fellowship.

With a consultant orthopaedic surgeon and a mechanical engineering colleague he redesigned the intramedullary nail in an aerospace alloy in the treatment of broken legs. He then went on to work with clinicians on the effects of age on the mechanical properties of human bone and tissue of the knee meniscus, and the mechanical causes of back pain. He became the co-founder and co-director of the Edinburgh Orthopaedic Engineering Centre. Intelligent flooring developed with D. Ross was described at the Science Museum. With an Edinburgh spin-off company he worked on the photo-bleaching of cataracts, thereby avoiding the need for surgery. This has now undergone successful human trials.

Books by McGeough include *"Principles of Electrochemical Machining", "Advanced Methods of Machining", "Micromachining of Engineering Materials" (Editor), "The Engineering of Human Joint Replacements".* McGeough is a Fellow of the Institution of Mechanical Engineers, of The Royal Society of Edinburgh, and of the Royal Academy of Engineering. From 2019-2020 he served as President of the Institution of Mechanical Engineers. Over 2020-2021 he chaired the Institution of Mechanical Engineers the COVID-19 taskforce supplying guidance to public bodies and industry on how to deal with the pandemic. The Royal Society of Edinburgh invited him to give an account of this work at its 2022 "Curious" programme. Other interests include gardening, golf and walking. He is a former holder of various Scottish County, Universities, and National Athletics championship awards, and a bronze medal winner at the Australian Universities Football Championships.

He is married to Brenda. They have 3 children and 7 grandchildren.

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Preface

On 22 May 2019, I became the 134th president of the Institution of Mechanical Engineers. I was following in the footsteps of Robert Stephenson, who had been the second president of the Institution; his father George, its first president, had sent him to Edinburgh University to take courses in the science subjects of physics, chemistry, geology and mathematics. (This was before engineering was established as a degree course at Edinburgh University). The Stephensons' realisation that a university education was needed if the younger Robert was to take over the mantle from his father, and in order to add scientific methods to the engineering and technology they possessed for their burgeoning locomotive and railway industry, must have stimulated the University to proceed to establish the Regius Chair of Engineering (firstly termed "Technology") at Edinburgh University with the approval of Queen Victoria. This was only the second Regius Chair of Engineering in the UK. (Glasgow University had established the first – the Regius Chair of Civil Engineering and Mechanics, following James Watt's invention of the steam condenser and its relevance to mechanical movement caused by steam).

The president of the Institution of Mechanical Engineers (IMechE) is expected to deliver an inaugural lecture following their election. Presidents sometimes choose to describe their career path, and how they achieved this office; others give an indication of how they anticipate the direction in which Mechanical Engineering should be going. Some of these addresses are highly technical, others less so.

In my case, and since I had been advised that most people could not recollect when there had been a president who was on the staff of The University of Edinburgh School of Engineering, I decided to prepare an address that included all such aspects. It would have an "Edinburgh" theme. As the audience would include people without the technical experience of mechanical engineers, it should be "popular science or engineering". It would include some of my own specialist topics, and since I have particular interests in manufacturing within mechanical engineering, that too had to play a part. Additionally, the cross-disciplinary aspects of engineering, which are crucial in today's landscape, also had to be considered. I also wanted to emphasise, especially for younger members, the need for perseverance in whatever they do.

Someone whom I had felt fitted these requirements was called Theo Williamson. He had been born, attended school, attended the University, and worked in Edinburgh. He had more than his fair share of setbacks and had to persevere. He was known initially for an invention dealing with sound reproduction, without making a penny from it, had anticipated the use of computers in machining, and furthermore revolutionised the way that the manufacturing industry operates. My own research on unconventional (electrochemical) machining was indirectly influenced by him (I had not even met him at the time) into its applications useful to the manufacturing industry. The title had to be attractive to a lay as well as a technical audience. In about the six weeks that it took when it looked like I would become President, the lecture on *"How Theo Williamson FRS changed 'The Sound of Music'"* was prepared to be delivered on 22 May.

I had enormous help from the IMechE staff in its preparation. They are too numerous to name, for which I apologise. I was fortunate too, in that I was able to draw on a presentation on the work of Williamson that I had given in 2018 to the Museum of Communication, Burntisland, Fife, as one of its series of Goudie Lectures, and also one to the Lothians Radio Society.

Prior to my election, the following members of the IMechE had endorsed my candidature: J. Atkinson, W. Edgar, D. Harrison, D. Hayhurst, S. Hinduja, K. Hussain, M. Lucas, J. McKnight, C Ó Brádaigh, J. Paul, D. Pham, Y. Qin, J. Simmons. The President (2018-2019) Tony Roche, spent much time briefing me on the duties and responsibilities expected of me. Subsequently, over 2019-2020, the Chief Executive, Dr. Colin Brown, and President-elect, Terry Spall, were most helpful and supportive, providing me with the benefit of the experience, as were the other members of the IMechE staff.

At the start of 2020, the coronavirus (Covid 19) started spreading throughout the world. At the IMechE, I chaired a Trustee Board meeting on 18 March, then that evening, put in place formally the arrangements for the forthcoming IMechE elections for May 2020. On 19 March, I travelled back by train to Edinburgh. I went into self-isolation for two weeks in a flat in the City found by my family in order to ensure that I did not carry the virus or transfer it. During those two weeks, I decided to use part of the time to put together this book on Williamson and to continue to do so on my return to our family home, as well as attending to IMechE business through “Teams” and the other media of the digital age, as all travel stopped.

It proved a daunting task. Williamson made outstanding contributions in several distinctly different fields. I have tried to capture the essence of

these achievements in the appropriate chapters. I am grateful to a number of specialists in the appropriate fields for verifying that I was making the right interpretation. To that end, I am most appreciative of the advice of Dr Brian Flynn, Professor Jim Murray (who had been an apprentice under Williamson at the Ferranti Company), Professor Duc Pham, Professor Tom Stevenson, and Mr Alasdair Williamson.

The diversity of Williamson's work has also prompted me to include a glossary of technology terms in the book. Dr Hanning Mai helped me to prepare it and with the calculations of the metric equivalent of the 'British Imperial System' of measurement, which were used in Williamson's time and in his publications. Both systems are included. Some figures and diagrams had to be redrawn, for which I wish to thank Dr Nan Yu. Industrial companies and enthusiasts associated with Williamson's work kindly supplied other photographs and diagrams.

The book has been typed by Diane Reid with contributions from Anna Allen and Alison Patton. I thank them for their patience and benefits of their skills. Professor Tom Stevenson, Chair of the Museum of Communication, Sarah Rogers at IMEchE Library and C. Kirby of IMechE liaised with me during the final stages of the preparation of the book. Thanks are due to Martin Byrne from The University of Edinburgh in arranging printed copies along with Chris Noden and Eddie Debourg for their expertise in production of the ebook.

Finally, I wish to express again my greatest thanks to my wife Brenda, and the other members of my family, Andrew, Karen and Ella McGeough, Elizabeth, Barry, Patrick, Thomas and Sophie Keane, and Simon, Louise, William, Amelia and Isabella McGeough, always steadfast supporters.

Chapter One:
Early Days in Edinburgh

1.1 Home Life

The Williamson family lived at Gilmore Place, in a large, solidly constructed, stone-built townhouse, formerly the manse of a nearby church, near the King's Theatre in Edinburgh. (Figure1.1)

Figure 1.1 Williamson's family home

This big house, which had three floors, required constant maintenance, which was undertaken mainly by Mr David Williamson senior, assisted, when necessary, by the rest of the family. Both parents had come from Ulster and settled in Edinburgh when they married. Mrs Ellie Williamson was of the old school and more British than the British. David Theodore Nelson Williamson was born on 15 February 1923. Figure 1.2 shows Williamson as a child with his sister Olive.

Figure 1.2 Williamson with his sister, Olive

Helping his father with the home jobs gave “Theo” practice in plumbing, wood and metal working, furniture making and DIY household repairs. The house was converted from gas to electricity and had anthracite stoves fitted in every room. Theo Williamson claimed that it was most certainly the best-heated house in Edinburgh, and the family enjoyed their father’s efforts, especially in the wintertime when most Edinburgh residents in their homes shivered in the cold.

Mr Williamson had a car-hire business with an impressive collection of fine cars. They were maintained almost entirely by him. He could strip and rebuild an engine. The coachwork would be brush-painted by him before spray painting was the norm. The finish that they were given would have put that on many modern cars to shame.

Mr Williamson’s health broke down in middle age, and he had to retire from the business. This made life difficult for Mrs Williamson, and on many occasions, only her very strong character carried her and her family through tough times.

At the age of five, Theo Williamson went to the local primary school, James Gillespie’s. (Figure 1.3)

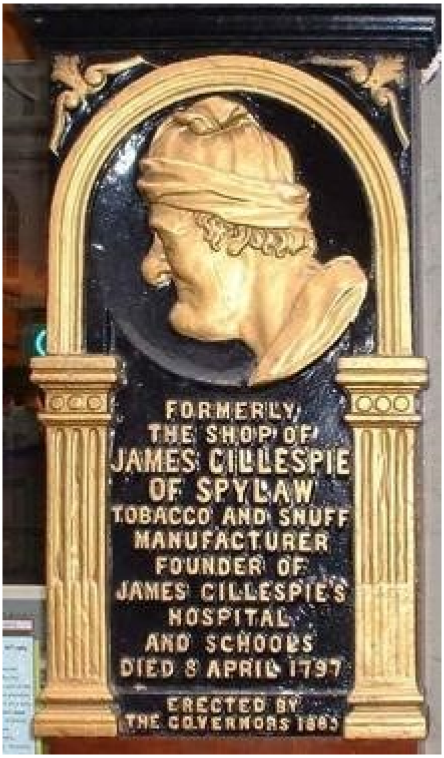


Figure 1.3 Plaque to James Gillespie – founder of Williamson's primary school

During his time there, he contracted tuberculosis (TB), apparently from a maid or home help. Weeks of rest were required. He would lie in bed, listening to the sound of the Edinburgh trams passing the King's Theatre, just up the street from the Williamson home. He was in and out of clinics but, fortunately, eventually recovered. Thereafter his health always gave his parents concern for his well-being. For the rest of his life, he only had marginal use of his lungs, owing to extensive scars that left him weakened physically.

His illness also led him away from physical activities and more towards reading, especially magazines like "Popular Wireless", to which his father subscribed. Articles on wireless design fascinated the young

Williamson. In 1932 his father constructed their first valve radio from a kit, the design of which was published in "Popular Wireless" authored by John Scott-Taggart. Every year thereafter, his father would construct the more recent circuit reported by Scott-Taggart. He would also build an appropriate piece of furniture on which it would be displayed. From his reading and helping his father, Williamson acquired the skills needed to make short-wave receivers and (albeit illegal) transmitters.

School friendships and exchanges with other radio enthusiasts were the foundations on which Theo Williamson's self-education in electronics was built. An article on negative feedback in another magazine prompted Williamson to build record-reproducing equipment with a 20W negative feedback amplifier that operated from the 200V direct current electricity supply used in those days in Edinburgh. Its performance was regarded by his peers as outstanding and representing the state of the art, the best that could be achieved at the time. Sound reproduction became part of Williamson's life from then on.

When a friend noticed Williamson's interest in science, he gave him a three-year subscription to "Popular Science", regarded as a practical version of "Scientific American". There were articles on practical aspects of physics, chemistry and electricity, and on how to construct modern equipment like mercury vacuum pumps, on "heavy water", and "luminescence". The articles fascinated him, so much so that he found out how to bind the copies of the magazine into a book; (as Michael Faraday had also done many years before in the 19th century when he worked in a book and newspaper shop).

With little interest in sport, Williamson's Saturdays were often spent at the Royal Museum of Scotland, especially its Science and Engineering section (in which, many years later, one of his engineering inventions was displayed). In 1935, a fascinating day at the Science Museum in London left an everlasting impression on him. He marvelled at displays of Man's progress from crude beginnings to sophistication in many scientific endeavours.

1.2 George Heriot's School

At the age of 12, Theo left James Gillespie's Primary School to start his secondary education at George Heriot's School, walking from Gilmore Place to his new school at Lauriston Place. (Figure 1.4)

Figure 1.4 George Heriot's School

The school had been founded in 1628 by George Heriot, a jeweller to King James the Sixth of Scotland and First of England, to provide education for poor and needy children. Its charitable status continues to this day. His progress there was steady and on the whole unremarkable, with two exceptions. He submitted an entry for the school's Miller Prize in Applied Science: on the radio transmission of power, showing how a motor could rotate at 100rpm at a distance of 10 feet[3m] from a radio transmitter. Much anguish went into this gadget. He used a small UHF (ultra-high frequency) transmitter at less than 0.5m wavelength, the energy being rectified by a silicon crystal of 1923 vintage. He built the motor from an aluminium disc containing a compass, made with an old AF (audio frequency) transformer winding of two to three thousand turns that was stationary at its periphery. He found an Osram LP2 triode oscillator valve with about six inches (150mm) long Lecher wires in the grid and anode, and it would only oscillate at UHF (ultra-high frequency) when its filament voltage was overrun by 50-100 per cent. Then it flared into oscillation, and its anode glowed red. Not being designed for such treatment, the life was hazardous, and money was short for replacements, even at second-hand prices.

When the coil was energised by the rectified UHF energy, the compass needle was attracted, and by pulsing the energy at the appropriate intervals, it was caused to rotate. It was a spectacular demonstration in those early days of radio.

The following year (1939), this time with two others, he was again awarded the Miller Prize (see Figure 1.5(a)). They made a lathe for recording gramophone records. Their ingenuity was impressive, adapting a recording cutter head made from an antique Bluespot balanced loudspeaker movement that dated back to the 1920 period. The exercise stood them in good stead, helping them to understand “drunken” thread forms in obtaining a good feed-screw mechanism.

The Headmaster reported that the various Special Prizes in 1938 for the session fell to be awarded to the following pupils namely:

Miller Prize in Applied Science:	David T.N. Williamson
	Robert S. Bowhill
	John J. Maconochie

Figure 1.5(a) Miller Prize awarded to Williamson (by permission of George Heriot’s School)

In 1937, the Williamson family took in Peter d’Eyncourt Stowell as a boarder; he stayed with them until he married two or three years later. Stowell was about 32, had a BSc degree from London University via Faraday House, and was an Associate Member of the Institution of Electrical Engineers. He had previously been with the LMS (London, Midland, Scottish) railway in London and had come to work for the Edinburgh Corporation Electricity Department as a Senior Engineer.

Peter and Theo immediately hit it off. Theo learnt that the boarder had been involved in the construction of a television receiver for the Marconi-EMI transmissions from Alexandra Palace in November 1936. They worked together to see if they could build a TV. Unfortunately, this was of no use in a city as far north as Edinburgh. Instead, they used the pieces to make an oscilloscope.

Stowell was a very innovative power engineer, always thinking of better ways of generating and distributing electricity and of new ways of power factor control and system measurement.

(During the War, whilst at the M-O Valve Company (see Chapter 2), Williamson designed and made for Stowell a very sensitive thermocouple with multiple elements in series, each group of elements separately heated within the vacuum envelope. Stowell used the apparatus to measure and chart the impedance of the Edinburgh distribution network by switching a heavy load onto the network at subsonic frequency (about 0.5 to one c/s), and using the thermocouples to detect the resulting RMS voltage and current fluctuations at another geographic point.

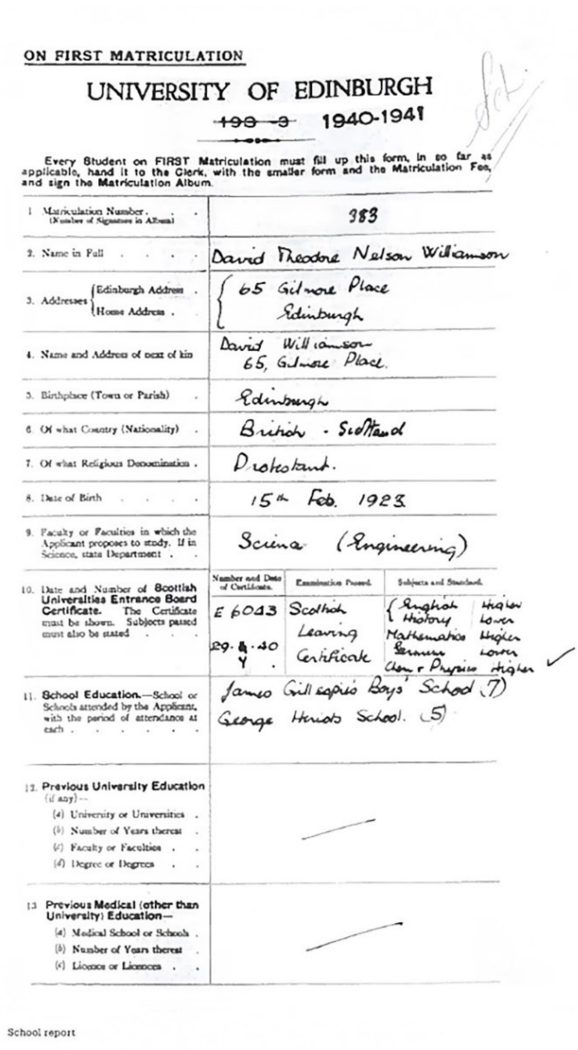
After the War, Stowell was instrumental in helping Williamson secure a job at Ferranti in Edinburgh. They continued to collaborate until Stowell left to become the Chief Engineer of the Merseyside and North Wales Electricity Board. (On his departure from Edinburgh, Stowell and Williamson continued to keep in touch, albeit less frequently, until tragically, the former died of a heart attack in 1964).

Williamson's exam records from George Heriot's School did not show anything remarkable about his academic prowess (Figure 1.5(b)).

German	12th	History	18th
Chemistry	19th	English	18th
Physics	20th	Handicrafts	1st
Mathematics	18th		

Figure 1.5(b) Examination results for DTN Williamson, place in class George Heriot's School class 5B 1938/39

However, his happy environment at home, his achievements with the Miller Prize, and Stowell's enthusiasm spurred Theo Williamson to gain the Scottish Higher passes needed to enter University, given in Figure 1.6.



ON FIRST MATRICULATION

UNIVERSITY OF EDINBURGH

~~193 -3~~ 1940-1941

Every Student on FIRST Matriculation must fill up this form, in so far as applicable, hand it to the Clerk, with the smaller form and the Matriculation Fee, and sign the Matriculation Album.

1. Matriculation Number. (Number of Signature in Album)	383
2. Name in Full	David Theodore Nelson Williamson
3. Addresses { Edinburgh Address / Home Address	65 Gilmore Place Edinburgh
4. Name and Address of next of kin	David Williamson 65, Gilmore Place.
5. Birthplace (Town or Parish)	Edinburgh
6. Of what Country (Nationality)	British - Scotland
7. Of what Religious Denomination	Protestant.
8. Date of Birth	15th Feb. 1923
9. Faculty or Faculties in which the Applicant proposes to study. If in Science, state Department	Science (Engineering)
10. Date and Number of Scottish Universities Entrance Board Certificate. The Certificate must be shown. Subjects passed must also be stated	Number and Date of Certificate: E 6043, 29.4.40; Examination Passed: Scottish Leaving Certificate; Subjects and Standard: English Higher, History Lower, Mathematics Higher, German Lower, Chem. & Physics Higher
11. School Education.—School or Schools attended by the Applicant, with the period of attendance at each	James Gillespie's Boys' School (7) George Heriot's School. (5)
12. Previous University Education (if any)— (a) University or Universities (b) Number of Years thereat (c) Faculty or Faculties (d) Degree or Degrees	—
13. Previous Medical (other than University) Education— (a) Medical School or Schools (b) Number of Years thereat (c) Licence or Licences	—

School report

Figure 1.6 University of Edinburgh Matriculation of Williamson (1940-1941)
(by permission from The University of Edinburgh)

1.3 Edinburgh University

In 1940, at the age of 17½, Theo Williamson began the BSc course in Engineering at The University of Edinburgh. (Figure 1.7)

Figure 1.7 Sanderson Building at The University of Edinburgh

It was wartime; students were required to perform fire watching and Home Guard duties, as well as the daytime and evening classes which were necessary. At The King's Buildings of the University, these were conducted in the Sanderson Building seen in Figure 1.7. The Labour

Prime Minister Ramsay MacDonald had opened the building in 1932. It represented state-of-the-art facilities for the time. The BSc course was a general one, encompassing civil, mechanical and electrical engineering.

The first two topics were covered at The King's Buildings. The classes gave Williamson a sound foundation in topics like hydraulics, strength of materials and heat engines which he was able to use later on in his career. For the electrical engineering subjects, mainly in the second and third years of the degree, he went to Heriot-Watt College (now University). Professor M G Say, its Head of Department of Electrical Engineering, and his staff gave Williamson a thorough grounding, especially in the practicalities of the subject. Indeed the teaching they provided was to stimulate Williamson and give him the inspiration needed for all that he faced in later life. (Figure 1.8).

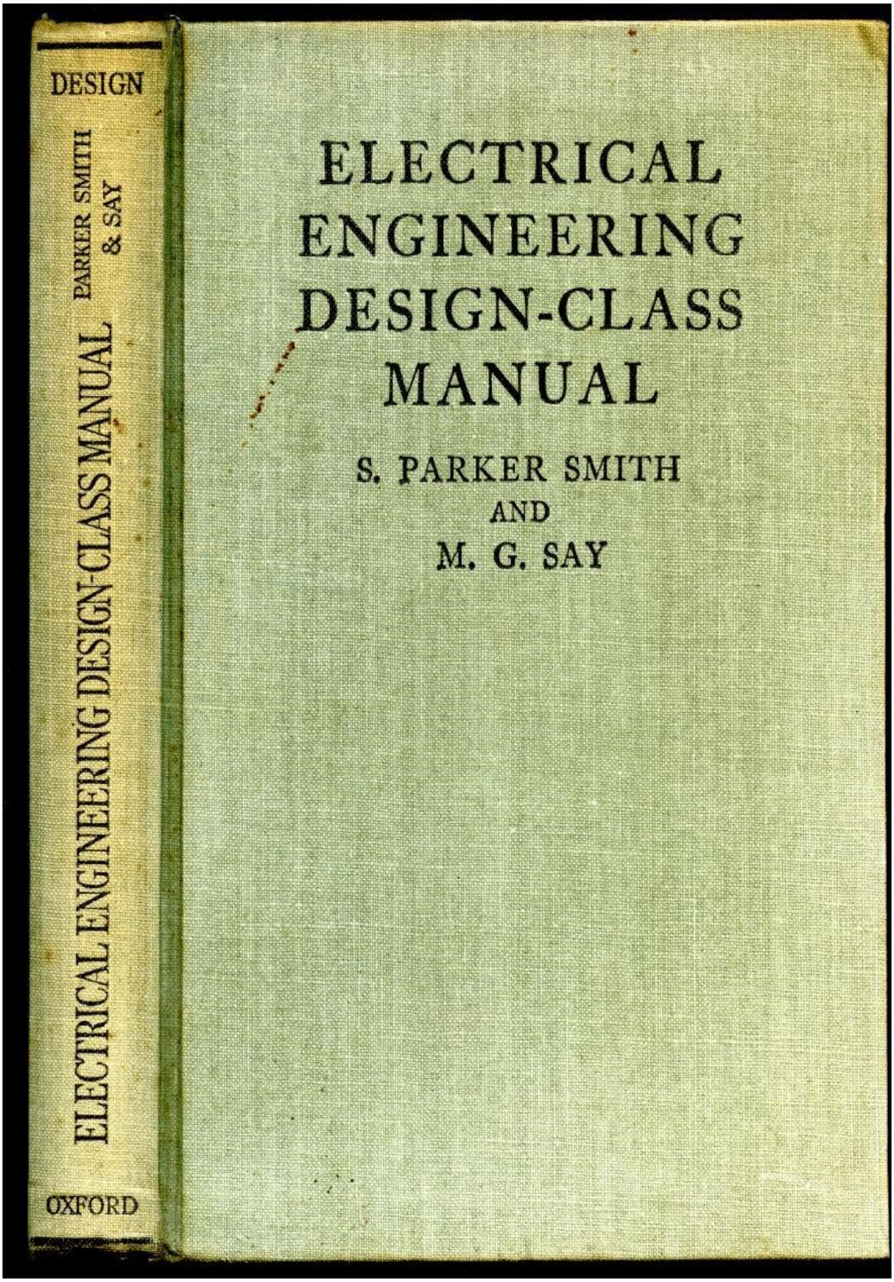


Figure 1.8 Professor Say's textbook on Electrical Engineering

This broadly-based engineering course gave him a real understanding of cross-disciplinary engineering, enabling him to talk knowledgeably with electrical and mechanical engineers without depending on input from more specialised colleagues. It thereby met his goals.

He sailed through the examinations in the engineering subjects. Unfortunately, Williamson's examination performance in Mathematics did not comply with the University regulations in place at that time. He failed the degree examination in his first year, in both May and the September "re-sits". He was permitted to carry the subject forward into the second year of the course, again passing the engineering subjects but again failing twice the Mathematics examination papers. A pass in Mathematics was required as mandatory. His performance in engineering subjects indicated that he was on a path to be eligible for an Honours degree. The failure in Mathematics meant that he left Edinburgh University in 1943 without a degree. See Table 1.1.

1941	Failed Technical Mathematics 1
1942	Did not appear for Technical Mathematics 2
1943	Failed Applied Mathematics, June, September
1944	Failed Applied Mathematics, March
1945	Failed Applied Mathematics, June

Table 1.1 Extracts from examination student record for D.T.N. Williamson

It would have been no reassurance for Williamson to know at this disappointing time that he was following in the footsteps of Robert Louis Stevenson (RLS). In the 19th Century, RLS studied Engineering at The

University of Edinburgh. He left without completing his degree and achieved international fame, albeit in a different field. Stevenson's father was a builder of lighthouses; he must have planned that, with an engineering degree, his son would enter the family business. RLS's career subsequently took a different path, becoming a poet and writer of books such as "Treasure Island" and "The Strange Case of Dr Jekyll and Mr Hyde". His Edinburgh University engineering experience must have had some effect on him as he subsequently wrote a book on the first Regius Professor of Engineering entitled *"Memoir of Fleeming Jenkin: Records of a Family of Engineers".* There is a statue of Robert Louis Stevenson at the entrance to Edinburgh Colinton Parish Church, pictured in Figure 1.9, where his grandfather, the Rev Lewis Balfour, was the Minister. The name David Balfour is a character in Robert Louis Stevenson's book 'Kidnapped'. (Some of the poems written by Stevenson are presented in the railings leading down to the church).

On the statue, the caption contains the below quotation from "Memories and Portraits" by Robert Louis Stevenson.

'Through my boyhood and youth, I was known and pointed out for the pattern of an idler, and yet I was always busy on my own private activity which was to learn to write. I kept always two books in my pocket, one to read and one to write.'

Figure 1.9 Robert Louis Stevenson studied Engineering at Edinburgh University

Because of Williamson's failure, he did not continue with his student membership in the Institution of Electrical Engineers, which would have duly led to him becoming a Chartered Engineer (CEng). (Many years later, when the Institution of Mechanical Engineers wanted him to be awarded one of its membership prizes in recognition of his "SYSTEM 24" achievements, it was not possible as he had been unable to join the IMechE, due to having no recognised engineering qualifications.

He was interviewed in his final year at the University by C. P. Snow, portrayed in Figure 1.10, later famous for his political and academic novels, but then the Chief Recruitment Officer for the Telecommunications Research Establishment (TRE), Malvern and the Government laboratories. Williamson related later that he was told by

Snow that he was not the kind of research engineer that they were seeking: "he could smell them a mile away, and Williamson was not one of them".

Figure 1.10 C. P. Snow interviewed Williamson (Courtesy of National Portrait Gallery)

The vestiges of the scarring on his lungs from tuberculosis that he suffered in his childhood also meant that Williamson was declared physically unfit for active military service. Instead, in 1942, he was drafted to the Marconi-Osram (M-O) Valve Company in Hammersmith, London, as an engineer in its Development Laboratory.

Chapter Two: The Williamson Amplifier

2.1 Valve Testing at M-O Valve Company

In the M-O Valve Company Development Laboratory shown in Figure 2.1, the design of new types of valves was being carried out by three or four specialists in the field.

Figure 2.1 M-O Valve Company

The overall aim was miniaturisation so that the valves could be used in aircraft. As a result, there was much trial and error testing. Williamson's task was to assist the specialists and do the testing of the valves. The work was mundane and tedious. Valve design did not interest Theo Williamson, although he was painstaking and conscientious in his duties. He was able to secure a transfer to the M-O Company's Applications Laboratory. There, he anticipated being able to make a more satisfactory contribution. This laboratory had at its head Graham Woodeville, who specialised in radio communication and in receiver valves. (Figure 2.2) It also had a specialist in the application of transmitting valves, H L Gibson. They and Williamson made up its three-person complement. Williamson readily took to this work, testing different types of circuits with new valve designs and preparing application reports on them so that they would be properly used.

Figure 2.2 Graham Woodeville

2.2 The Williamson Amplifier

When allocating valves that had to be tested for the day, Woodeville let the young Williamson use any spare time remaining to try out his ideas on a new kind of amplifier to improve sound reproduction and to do some work on a very light-weight gramophone pick-up, which was not commercially available. The outcome was an amplifier unit that yielded 20W at less than 0.1 per cent harmonic distortion. (At that time, most amplifiers had a rating of about 5 per cent harmonic distortion).

The high qualities of this amplifier with a lightweight pick-up, both described below, and an improved loudspeaker assembled from components that Woodeville had built for his audio testing, gave rise to sound reproduction of a quality that hitherto had never been achieved.

It was demonstrated to many visitors to the laboratory.

Woodeville's boss asked for a demonstration by Williamson to the Board of the M-O Valve Company. He was instructed to write a report, No. Q253, on his invention.

Figures 2.3 (by permission of "Wireless World") and 2.4(a), (b), and (c) below show the Williamson Amplifier Circuit.

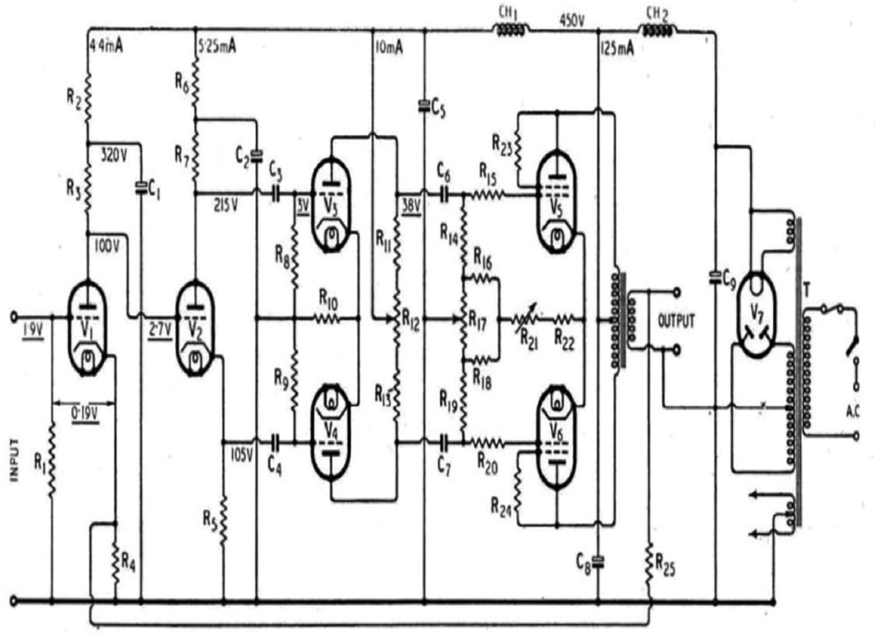


Fig. 5. Circuit diagram of complete amplifier. Voltages underlined are peak signal voltages at 15 watts output.

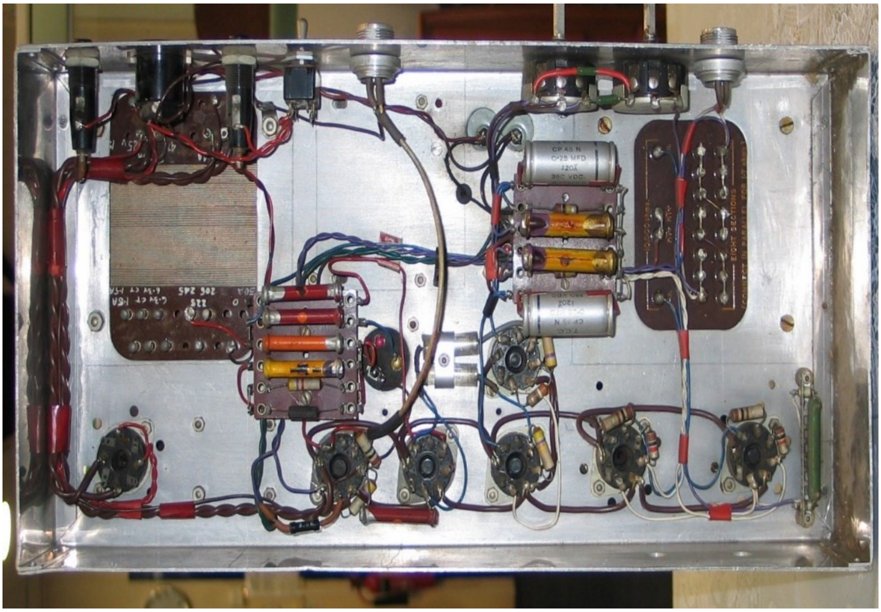
CIRCUIT VALUES.

R_1	1 MΩ $\frac{1}{4}$ watt ± 20 per cent	R_{15}, R_{20}	1,000 Ω $\frac{1}{4}$ watt ± 20 per cent	C_8	8 μF 550 V, Wkg.
R_2	33,000Ω 1 watt ± 20 „	R_{16}, R_{18}	100Ω 1 watt ± 20 „	C_9	8 μF 600 V, Wkg.
R_3	47,000 Ω 1 watt ± 20 „	R_{17}, R_{21}	100Ω 2 watt wire-wound variable.	CH_1	30 H at 20 mA (Min.)
R_4	470 Ω $\frac{1}{4}$ watt ± 10 „			CH_2	10 H at 150 mA (Min.)
R_5, R_6, R_7	22,000 Ω 1 watt ± 10 „	R_{22}	150Ω 3 watt ± 20 „	T	Power transformer. Secondary 425-0-425 V, 150 mA (Min.) 5 V. 3A, 6.3 V. 4A, C.T.
R_8, R_9	0.47 MΩ $\frac{1}{4}$ watt ± 20 „	R_{23}, R_{24}	100 Ω $\frac{1}{2}$ watt ± 20 „		
R_{10}	390 Ω $\frac{1}{2}$ watt ± 10 „	R_{25}	1,200 $\sqrt{\text{speech coil impedance}}$, $\frac{1}{4}$ watt.		
R_{11}, R_{13}	39,000 Ω 2 watt ± 10 „				
R_{12}	25,000 Ω 1 watt wire-wound variable.	C_1, C_2, C_5	8 μF 450 V, Wkg.	V_1 to V_4	L63
		C_3, C_4	0.05 μF 350 V, Wkg.	V_5, V_6	KT66.
R_{14}, R_{19}	0.1 MΩ $\frac{1}{4}$ watt ± 20 „	C_6, C_7	0.25 μF 350 V, Wkg.	V_7	U52.

Figure 2.3 Williamson Amplifier Circuit (by permission of "Wireless World")

(a)

(b)



(c)

Figure 2.4 (a, b, c) Front, back and underside of the Williamson Amplifier (courtesy of Museum of Communication)

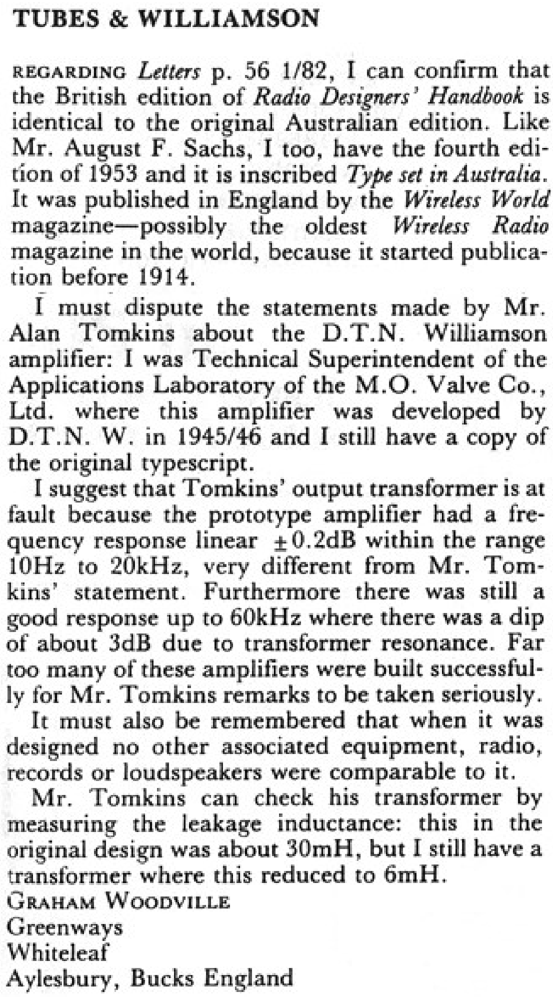
After Williamson had left the M-O Valve Company, the report was duly given to the editor of “Wireless World”, by F.E. Henderson, head of valve sales at the parent G.E.C. Company in Kingsway. Williamson had specified G.E.C.’s valves in the design: publicity for the amplifier might thereby increase sales of their valves.

The editor was already familiar with Williamson as he had previously written articles for the magazine. Details of the “Williamson Amplifier” were published in “Wireless World” in 1947 and 1949, reproduced in Figure 2.3, with the magazine describing the circuit as the accepted standard for high-fidelity reproduction.

The article was an immediate success. Hundreds of thousands of amplifiers, based on Williamson's design, were built worldwide by both amateurs and entrepreneurial companies. In the USA, more than 100,000 Williamson amplifiers were sold by one company.

Since the design had been published, these, and other sales, brought no income to Williamson. The article, however, gave him international recognition. In later life, especially when in the USA on business, he attended meetings with people who had built a Williamson Amplifier ten years earlier.

In Australia, the magazine "Radiotronics", in its November-December 1947 issue, described it as "by far the best we have ever tested". On the other hand, it had its critics. They were promptly refuted by Woodeville himself in a letter to "The Audio Amateur" in 1982 (Figure 2.5).



TUBES & WILLIAMSON

REGARDING *Letters* p. 56 1/82, I can confirm that the British edition of *Radio Designers' Handbook* is identical to the original Australian edition. Like Mr. August F. Sachs, I too, have the fourth edition of 1953 and it is inscribed *Type set in Australia*. It was published in England by the *Wireless World* magazine—possibly the oldest *Wireless Radio* magazine in the world, because it started publication before 1914.

I must dispute the statements made by Mr. Alan Tomkins about the D.T.N. Williamson amplifier: I was Technical Superintendent of the Applications Laboratory of the M.O. Valve Co., Ltd. where this amplifier was developed by D.T.N. W. in 1945/46 and I still have a copy of the original typescript.

I suggest that Tomkins' output transformer is at fault because the prototype amplifier had a frequency response linear ± 0.2dB within the range 10Hz to 20kHz, very different from Mr. Tomkins' statement. Furthermore there was still a good response up to 60kHz where there was a dip of about 3dB due to transformer resonance. Far too many of these amplifiers were built successfully for Mr. Tomkins remarks to be taken seriously.

It must also be remembered that when it was designed no other associated equipment, radio, records or loudspeakers were comparable to it.

Mr. Tomkins can check his transformer by measuring the leakage inductance: this in the original design was about 30mH, but I still have a transformer where this reduced to 6mH.

GRAHAM WOODVILLE
Greenways
Whiteleaf
Aylesbury, Bucks England

Figure 2.5 Letter from Woodeville defending Williamson (extract from the original letter)

Many years later, writing in "Electronics World" in September 1996, a music enthusiast, Linsley Hood, summarised the technical qualities of the amplifier and commented that during the war and post-war years, the improvement in audio quality of gramophone records and the associated quality of a.c. mains-powered audio amplifiers had been extensively investigated; he cited Williamson, who had dismissed criticisms that the use of push-pull output stage layouts were inadequate.

Hood pointed out that most valve-operated power amplifiers required an output transformer to match the relatively high output impedance of the valve output stage to the low impedance load presented by the loudspeaker. The transformer was usually the most difficult and costly part of the system to design and build. At that time, intrinsic signal distortion of a valve amplifier could range from about 0.5 to 10 per cent. Attempts had been made to reduce this intrinsic distortion by applying local negative feedback in various amplifier designs; however, the output transformer remained the major source of transfer and frequency response non-linearities.

Linsley Hood then describes Williamson's articles in "Wireless World" from 1947 to 1949. There, he had introduced a high-quality audio amplifier design. He used a G.E.C. "kinkless tetrode" output valve, the KT66. The single overall negative feedback loop covered both the whole of the amplifier and the loudspeaker output transformer. The feedback resistor R25 in Figure 2.3 connects the loudspeaker terminal on the output transformer back to the cathode of V1, the first valve at the input. With one exception, Williamson used triode amplifier valves: they had a lower intrinsic distortion figure. (The exception was the triode-connected KT66 output valves). He also used local negative feedback from un-bypassed cathode-bias resistors, which eliminated the need for electrolytic bypass capacitors. Non-polar, instead of electrolytic high-tension reservoir (C9) and smoothing capacitors (C8), were also employed in order to provide more consistent a.c. behaviour (electrolytic capacitors were less well developed at that time).

Williamson's design showed that overall negative feedback could be applied without causing either high or low-frequency instability. His design overcame difficulties previously encountered on the quest for high-quality sound reproduction.

His design yielded performance that was better than 0.1 per cent harmonic distortion at 15W output from 20 Hz to 20kHz. The ±1 dB bandwidth ranged from 10Hz to 100kHz.

The editor of "Wireless World" subsequently wrote "…the "Williamson" has been widely accepted as the standard of design and performance whenever amplifiers and sound reproduction are discussed. Descriptions of it have been published in all principal countries … its widespread reputation is based solely on its qualities".

Williamson himself gave a lecture to the B.S.R.A. Convention (British Sound Recording Association) in May 1953, in which he provided further details of his approach and how his lightweight pickup was developed for gramophone records. Signal imperfections or noise could be divided into two main classes: that arising from the granular structure of the record material causes a steady "hiss" of "white" noise, encountered often on the 78 r.p.m. records popular at that time. His amplifier was designed to overcome this kind of noise. The second type of noise stemmed from dust and surface defects on the disk. The lightweight pickup developed in conjunction with the amplifier was based around the shape of its stylus, which has a considerable effect on the quantity and the type of this so-called "impulse" noise. He replaced the more common spherical type of stylus of 0.0025 inch (0.064 mm) radius with an elliptically-shaped one with a radius of curvature at the point of contact of 0.0006 inch (0.015 mm), which reduced the noise level by 3-6 decibels and also enhanced the quality at the higher frequencies needed for recorded music.

2.3 G.E. Research Laboratories

Towards the end of Theo Williamson's time at the M-O Valve Company, he was able to spend a few weeks at the General Electric Company (G.E.C.) Research Laboratories, Wembley. This G.E.C. research and development laboratory had been run, from its beginning, by Clifford C. Paterson FRS; it was generally regarded as the best industrial laboratory of its kind in the UK, comparable with the Bell Laboratories in the USA and the Philips counterpart in Eindhoven, Holland. Its activities ranged from equipment for streetlighting to advanced electronics.

Williamson was allocated to the group led by Dr E.G. James, who was investigating the physics of valves and vacuum devices. Although he was not there long enough to learn or do very much, the laboratories left him with a lasting impression of the stimulating atmosphere of innovative thinking and action that Paterson had created and the idea of how a model industrial research and development laboratory should be run.

At the end of the War in 1945, Woodeville wanted Williamson to stay on at the M-O Valve Company. The Decca Company also offered him several jobs, from their acquaintance with him and his achievements in sound reproduction. He decided instead to return to Edinburgh, where, in 1946, he took a job as a Development Engineer with the Ferranti Company.

Chapter Three:
Ferranti Ltd. Edinburgh

3.1 Background

The Ferranti factory in Edinburgh had been built in 1943 for the manufacture of the gyro gun sights fitted to all British fighter aircraft. Figure 3.1 shows its main building at that time.

Figure 3.1 Ferranti headquarters in Edinburgh, 1946 (Courtesy of David King)

3.2 John Toothill

The general manager of the Edinburgh factory was "Jack" (later Sir John Norman) Toothill, Figure 3.2.

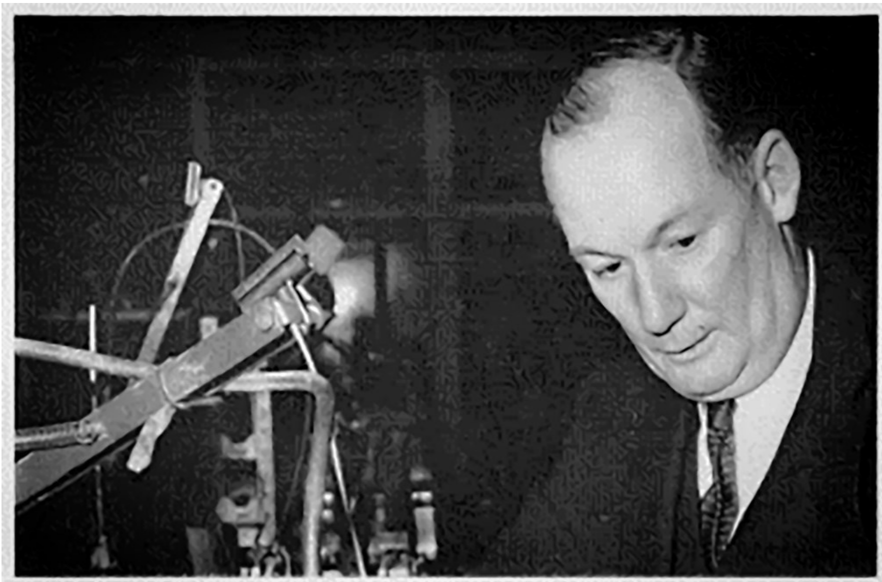


Figure 3.2 Sir John Norman Toothill, General Manager 1942-1968, Director, Managing Director to 1975

He had initially trained as an engineering apprentice but soon felt that he was not cut out for that kind of work and transferred his skills to Accountancy. Toothill had charisma and a keen intellect, and his personal understanding of engineering provided him with the background to handle both engineers and managers, who often had differing views.

An outstanding leader, he eventually became the managing director of Ferranti, Scotland. He conducted its business in a friendly and firm fashion, which its staff recognised and respected, giving of their best. Under Toothill, the factories in Scotland, over the next 30 years, rose to become the most profitable of the Ferranti group. He was also greatly instrumental in the efforts to change the Scottish engineering focus from a heavy, low-added-value base to one that was electronics-focused.

Toothill brought Maurice Kenyon Taylor to Edinburgh from the Radio Department of the Ferranti factory in Manchester, where he had worked since the 1930s. Maurice Taylor had run the manufacturing of the I.F.F. (Identification Friend or Foe) apparatus installed in British military aircraft in the War. He was noted there for his ingenuity and inventiveness. His job in Edinburgh was to run an Applications Laboratory, recently established with a view to exploiting for peaceful purposes the knowledge acquired by Ferranti during the War.

3.3 Applications Laboratory

Williamson was appointed to Taylor's Applications Laboratory. He found him to have an immensely inventive mind. Taylor was to become the second, most influential person in Williamson's professional development, following Woodville at the M-O Valve Company. In their meetings, Taylor would throw out more ideas to his staff in 30 minutes than most people could do in a year. Theo Williamson initially found this disconcerting and confusing for himself and the other members of the Laboratory. His colleagues realised that Taylor's ideas required much subsequent thought, but through the initial state of confusion, they soon found themselves being stimulated also to think innovatively and "outside the box".

The Applications Laboratory team devoted about four years to applying measurement and control techniques acquired in wartime to textiles, an industry that was predominant in the Manchester area where the Ferranti Company was established. Williamson himself regarded the solutions to technical problems associated with textiles as relatively trivial and of little use to an industry that was already declining.

Moreover, the amount of effort needed to provide this technical support for the textile companies, to improve the equipment in the few applications in which they could afford to invest, also meant that little significant income was generated for Ferranti.

The Applications Laboratory, therefore, became directed more to the Ministry of Supply work. Williamson's first big project was the development of an ultrasonic airspeed indicator, and next an ultrasensitive magnetic amplifier that had emanated from ideas of Professor F.C. Williams. (The latter is discussed more fully in the next chapter). Theo Williamson's second big job was the instrumentation of the prototype steam catapult for the aircraft carrier, "Perseus". This equipment was being installed at Rosyth Naval Dockyard by the Edinburgh firm Brown Brothers under the direction of Commander Colin Mitchell of the Navy. The installation was completed in 1950.

In that year, Maurice Taylor was seconded to Ferranti Electric Ltd, Canada, in order to establish a development laboratory; he decided to settle in Canada.

About this time, Toothill came to see Williamson, telling his young development engineer that he wanted Ferranti to devote more effort to improving the firm's own manufacturing techniques. By then, the company's Instrument Laboratory, which had developed the Gyro Gun Sight, had branched out into aircraft fire control; and a separate Radar Laboratory had been formed under John Stewart from T.R.E. (Telecommunications Research Laboratory).

Their activities required the manufacture of a wide variety of mechanical parts. These demands on the Ferranti workshops, especially in milling, were leading to congestion and lengthy delays in the time needed to make them. Complex waveguide assemblies for aircraft radar had to be carved out of a solid piece of aluminium alloy, and the time needed to machine to the high degree of precision required was astronomical.

Chapter Four: Ferranti System of Computer-Controlled Machining

4.1 Background

At Manchester University, Professor F.C. ("Freddie") Williams, depicted in Figure 4.1, was vigorously pursuing research into computer science and its applications. (Williams had graduated B.Sc. from the University of Manchester, Department of Engineering in 1932). He was awarded a Ferranti Scholarship to undertake a D.Phil (in 1936) at Oxford University. During the Second World War, Williams made major contributions to I.F.F. (Identification Friend or Foe), Airborne Interception (AI) and "Oboe" systems. I.F.F. let radar operators distinguish between friendly and enemy aircraft; with AI, aircraft could automatically track and intercept other aircraft. "Oboe" was a precision ground-controlled blind-bombing system. He returned to the University in 1946 as a Professor in the Department of Electro-technics (later renamed Electrical Engineering). Williams and his group researched the storage of binary digital information on cathode ray tubes (CRT). The "Williams Tube" was the outcome. Around this, he and his principal co-worker, Kilburn, designed a computer with electronic storage for both program and data. An experimental machine ran its first program in 1948. A useable computer, the "Manchester Mark 1," was duly designed, built and operated the following year. The Ferranti Mark 1 computer is shown in Figure 4.2.

In conjunction with Williams and his staff, including Alan Turing (Figure 4.3) who had moved from Bletchley Park to Manchester

University at the end of the War, and the National Research Development Corporation (NRDC), the Ferranti Company built the world's first commercial computer and established a department to develop computer technology for their industrial needs.

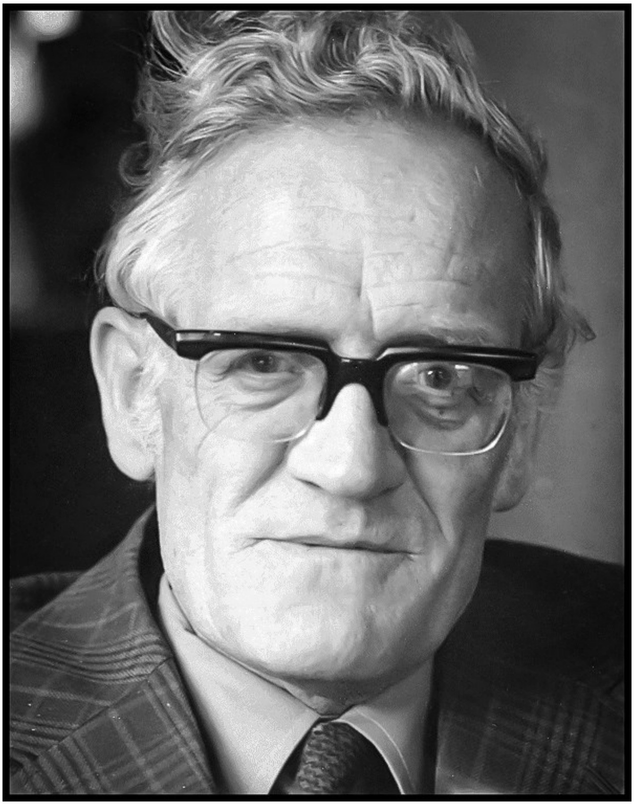


Figure 4.1 Professor F. C. Williams of Manchester University

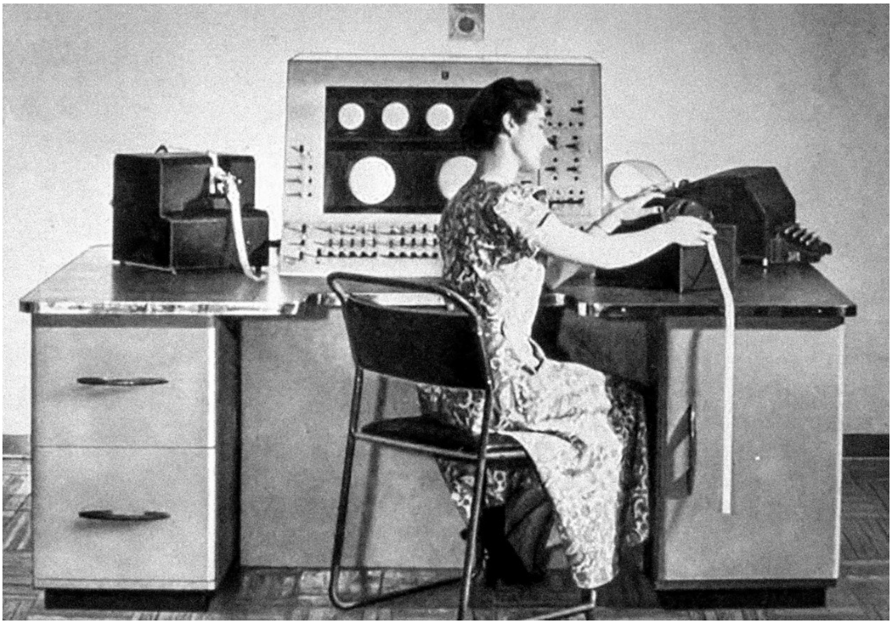


Figure 4.2 Ferranti Mark 1 Computer (Courtesy of the Computer History Museum)

Figure 4.3 Alan Turing statue at Manchester University (Courtesy of University of Manchester)

Williamson quickly realised that computer technology could be a ready answer to Toothill's instructions to him. It could be applied to small batch manufacture, especially to metal cutting, for the components Ferranti had to make.

If the slideways of machine tools could be moved by servomechanisms, controlled by a computer, it might be possible to machine components by this form of control, instead of the process being dependent on the manual skills of an experienced machinist.

He gathered together a group from the Applications Laboratory, initially of about five people, to work on the idea. Figure 4.4 shows the group. Few of them had much, if any, experience in such computer-related technology, yet they were being expected to advance Ferranti's machining capability beyond the traditional methods.

Figure 4.4 Williamson's group from Ferranti (left to right: John Irvine, Peter Walker, Donald Walker, Owen Stainsby, Jim Holmes)

They would have been more acquainted with procedures in which a machinist would work from a drawing on which the dimensions of the part to be made were specified. The machinist would fix initial settings on the machine tool in so far as it was possible, if necessary, re-set the positions during the process. Throughout the entire operation, the work would have to be checked regularly. There would be frequent reference to the engineering drawing so that all the required procedures had been performed to produce the object needed.

4.2 Numerical Control

4.2.1 Basic Principles

The Ferranti group were now to investigate numerical control (NC) of the machine tool. The steps they had to learn in those first days of this innovative computer technology were summarised by Gilbert, as part of his address as President of the Newcomen Society, in the Tenth Dickinson Memorial Lecture on "The Control of Machine Tools – A Historical Survey" in 1972. (Dickinson had been a former President and keeper of the Mechanical Engineering Collection of the Science Museum, which, as noted in Chapter One, Williamson had visited as a schoolboy.) Gilbert described how the information in the engineering drawing could be extracted in the form of a sequence of numbers. The numbers would be fed into the machine tool as electric pulses, making it perform in the manner required.

Each point on the surface of the part to be made could be represented by its three coordinate numbers (x, y, z), as specified in the engineering design. They would be in the decimal system to the scale of ten. Thus, a number such as 1951 would be indicated by $1 \times 10^3 + 9 \times 10^2 + 5 \times 10^1 + 1 \times 10^\circ$.

A decimal number may require as many as ten symbols: 0 1 2 3 4 5 6 7 8 9 to register it. Such a number cannot be used for numerical control. It has to be converted into a binary form in which only two numbers are used. In binary counting, after numbers 0 and 1, the next one, 2, to the scale of 2 becomes 1, 0. The number 3 becomes 1, 1. Number 4 is 1, 0, 0. The number 5 is given by 1, 0, 1; 6 is 1, 1, 0. Number 7 is 1, 1, 1.

For example, the decimal number 45 which is $4 \times 10^1 + 5 \times 10^0$ is the same as $32 + 0 + 8 + 4 + 0 + 1$. This equals $1 \times 2^5 + 0 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0$.

Thus, in the binary system, the number 45 is represented as 1 0 1 1 0 1.

As binary numbers are only comprised of two digits, they can be represented and stored on a punched tape. For example, where hole drilling is required, a hole would be represented by 1, and the absence of a hole by 0. The numbers on the punched tape could also represent the coordinates of the position of the machine slides.

4.2.2 Application of Binary System to Machine Tool Control

The numbers on the tape could also be used to signify feed rate, spindle speed, and even commands that could be delivered to automatic tool-changing facilities. The machine tool could also be fitted with sensors. Signals from these could be fed to a servomechanism, thereby providing instructions for any machining that was required.

The team at Ferranti first had to work out how the slideways in a milling machine could be driven to the 0.0002 inches (0.0051mm) precision required. Initially, they used Velodynes, which F.C. Williams had developed during the War, for velocity following. However, the motors available in 1950 were war surplus and had inadequate power for machine tool work. They proceeded to develop a variety of servomechanisms, utilising magnetic amplifiers and high-frequency induction motors, which were capable of very rapid acceleration.

The team realised that high and variable slideway friction, and backlash in the lead screws, were the main problems that had to be addressed and solved.

Various machine tool drives, depending on the size of the tools and the applications for which they were to be used, were tried over the following five years to overcome these problems.

4.3 Re-circulating Ball Screws

As the work progressed, the limitations of the lead screws normally used for these applications became apparent. They learnt that in the USA, the Beaver company was manufacturing an alternative: re-circulating ball screws of length about 3 feet (1 m) of high efficiency, although not without backlash. These devices were adopted by the Ferranti group. Their efficiency was sufficiently high to let two nuts be spring-loaded against each other. This method of screw transmission more than served Ferranti's needs. For longer machines, the group also devised a rack and pinion drive system incorporating a split or double pinion, spring-loaded to remove backlash. They had now overcome most of the mechanical difficulties.

Word reached Williamson in 1951 that Professor Gordon Brown at Massachusetts Institute of Technology (MIT) was also investigating servomechanism control of machine tools. He arranged a visit to him. Williamson came away concluding that they had nothing to teach him that might be useful to the Ferranti effort. For the Ferranti production requirements, he needed to drive the slideways in a milling machine to an accuracy of 0.0002 inches (0.0051mm), which the MIT servomechanisms could not deliver at that time.

4.4 Digital Differential Analyser (DDA)

The Ferranti Computer Department was envisaged as providing the data processing needed for the machine tool control. It would prepare the computer programs supplying the digital control data for the machine tool servomechanisms. The Ferranti Mark 1 computer was assessed for this purpose; however, the team concluded that it would be too slow, with most of its time being taken up delivering information to a single machine tool, leading to higher inherent costs.

Instead, the Chief Engineer of the Ferranti Machine Tool Control Department, Donald Walker, devised a new approach, a “Digital Differential Analyser (DDA)”, with a hard-wired program. This method solved quadratic equations associated with the generation of circles, ellipses and parabolae in three dimensions. These were the shapes required in engineering design for manufacturing the parts needed at Ferranti.

Williamson’s group proceeded to construct a machine based on Walker’s idea. By using logic elements made of diodes followed by a micro-miniature valve amplifier, they were able to generate control data at a speed ten times faster than was required for the slideways of the machine tool.

The data were also now transferred to the machine tool from magnetic tape instead of punched paper tape. The transfer of data was faster and smoother and no longer placed limits on the speed of machining. It also saved the use of electronic valves and transistors at the machine tool.

A new computer system based on the DDA was duly developed that could accept the minimum data needed to make a component. It translated this information into the slideway distance and speeds required for the machining of the component at a higher rate of machining than was previously possible.

The machine tool control group were now installed in a house at Craigroyston near to the Forth with its own manufacturing space (Figure 4.5).

(One of Theo's friends, a surgeon, found himself a bit short of cash when employed in the very new National Health Service just after the war. To augment his income, he sold chickens and persuaded his friends to assist in the enterprise. Thus came Theo to Craigroyston House, armed with chickens for sale to his colleagues! All went well – at least there were no records of complaints – until one Monday when it became too obvious that all of the chickens had not been sold or removed by the previous Friday).

Figure 4.5 Craigroyston House, Edinburgh

They produced the DDA in the computer room at Craigroyston, and a tape service for Ferranti machines throughout the UK was supplied by them. They duly produced a further system that let bigger users have their own tape facilities. With this development, clients with their own digital computers were able to make an intermediate tape. This tape was fed into a small DDA from which the final machine tool control tape was made.

It should be noted that although Williamson’s team developed the DDA, B.J. Wood at the main Ferranti Computer Department at Moston produced the “PROFILEDATA” program. With this program, menus could be extracted and assembled. They eased, for example, the cutting of ships’ plates, where various apertures were often repeatedly used).

Wood's development became the most profitable part of the Ferranti part-programming business.

With all this work in progress, the question of accurate control of the machine became paramount. The entire system was to be controlled by a digital computer. Williamson decided that lead screws, which were then the main way by which measurement of machining operations was performed, could not be depended on to provide the high level of accuracy needed for their precision computer-controlled machine tools. These traditional measurement methods, essentially based on mechanical principles, could be adversely affected by dust, tooth ripples, variations in oil film thickness, etc.

An entirely new approach to measurement was needed. A novel diffraction grating system was to emerge. The Ferranti team was about to enter further fresh technological fields.

Reference

Gilbert, K.R. (1971-1972). "The Tenth Dickinson Memorial Lecture, The Control of Machine Tools – A Historical Survey". Trans. Newcomen Society, pp.119-127.

Chapter Five: Diffraction Grating Measurement System

5.1 Background

Up to this time, lead screws fitted to the milling machine were the main way by which measurements of the machining operation were undertaken. These were considered unsuitable for digital, computer-aided operation, which required machining to close tolerance.

An entirely new approach was needed in which measurement would be superior to the accuracy at which the machine tool could perform.

5.2 National Physical Laboratory (NPL)

Williamson's team investigated a form of linear measurement with line counting and photographic plates, as done in screen printing. When two such plates were superimposed, Moiré fringe effects could be produced. Gratings of about 5000 lines (L) per inch (~200L/mm) were needed. Williamson and a colleague sought the advice of Dr H. Barrett, Superintendent of the Metrology Department at the National Physical Laboratory, who referred them to Dr L.A. Sayce, Superintendent of its Light Department. Dr Sayce had been investigating the production of large optical interference gratings of about 14000 lines per inch (~560L/mm), using techniques which had been suggested to him by Sir Thomas Merton. His team were using a helical screw and a pith nut; the relatively soft nut was driven by the screw rotation averaging out all the cylindrical errors in the thread. The outcome was effectively a perfect linear motion. By this method, a second screw was cut, having a virtually perfect linear pitch. The thread angle was selected in order to provide the best optical diffraction properties. A plastic film was poured over the screw. It was then cut and peeled off to produce a cast, which in turn was transferred to a piece of glass. A highly accurate replica optical grating, relatively cheap to make, was thereby obtained.

Sayce and his colleagues duly produced threads of 5000 lines per inch (200 L/mm) and replicas which were of high accuracy. A pitch of exactly 5000 lines per inch (200L/mm) was achieved by tilting the grating at a slight angle to the line of movement. A piece of this grating was then used as a cursor in the production of a magnified Moiré fringe pattern, with a single fringe moving forwards or backwards in accordance with the relative movement of the cursor and the main grating. A movement of 0.0002 inches (0.00508 mm) was determined by one complete fringe cycle. They used two photo-diodes to obtain two sinusoids in quadrature; the direction of the vector rotation corresponded to the backward and forward movements. Further work on a logic system enabled a pulse train of 10000 pulses per inch (393.7 pulses/mm) to be achieved, which gave positive or negative pulses, depending on the direction of movement.

Grating lengths up to about 12 inches (304.8 mm) were found to work well. Above this size, shorter lengths were assembled in accurate register up to about 60 inches (1524 mm). For longer lengths beyond 60 inches (1524 mm), a reflecting system with photographically printed and etched lines on polished stainless-steel tape was devised based on the same methods.

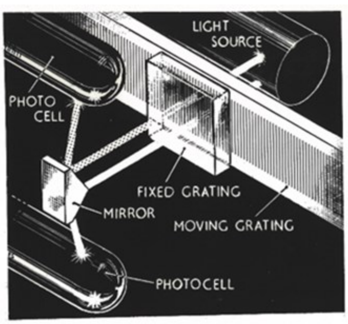
As previously mentioned, the Ferranti team adopted the recent advancement of high-efficiency recirculating ball screws. They achieved screw transmission backlash performance, which was an order of magnitude better than that of any other mechanism, by spring-loading two nuts against each other.

These activities now meant that the mechanical problems were essentially overcome. The scene was set for Ferranti to manufacture high-precision machine tools, using a novel measurement system as summarised next.

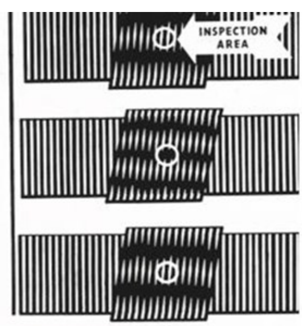
5.3 Principles of Measurement System

Figure 5.1(a, b, c) illustrates how this system of measurement works. Its key feature is an optical diffraction grating. The grating has a line structure which carries an accurately known number of lines per mm (or inch). The direction of these lines is perpendicular to that of the length of grating.

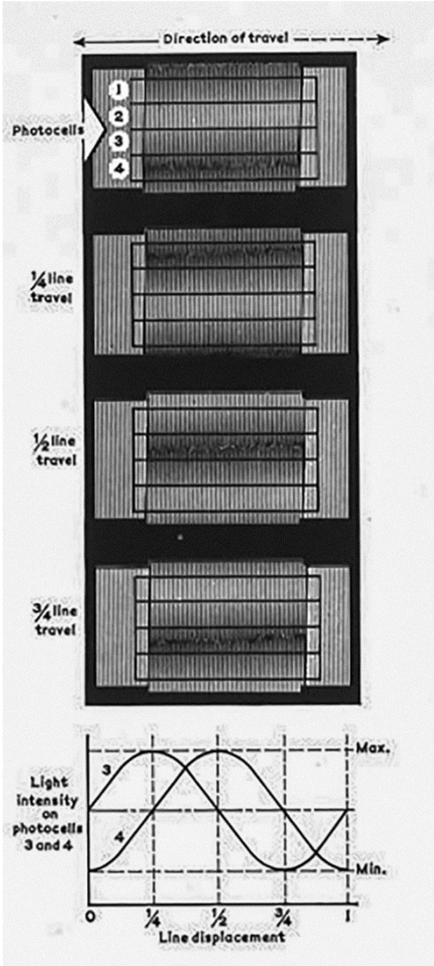
Figure 5.1 Diffraction Grating System



(a)



(b)



(c)

Two sections of the grating are superimposed; one is tilted at a small angle to the other. This configuration results in the production of a Moiré fringe pattern. The pattern effectively exhibits a sinusoidal distribution of light intensity due to the integrated interference effects emanating from the angular intersection of the individual lines on each of the gratings. The pattern is, in effect, a magnification, having facilitated the separation of the individual lines of the diffraction grating.

One grating is moved relative to the other and perpendicular in direction to its line structure. The fringe pattern then moves at right angles to the direction of travel. The "sense" of its movement is dependent on the direction of relative travel of the two gratings. As illustrated in Figure 5.1(b), inspection of a small section of the fringe pattern indicates the relative movement of one line width on the gratings, allowing one entire cycle of light and darkness on the interference pattern to pass the region being examined.

The individual dark and light bands can be detected, as their width can be made sufficiently great to enable detection by a photo-sensitive device, such as a photocell.

The photo-sensitive element is used to define the position of a particular point, and the number of dark and light bands that pass this point are counted. If the number of lines to the inch (25mm) is known, the amount of displacement of one grating with respect to the other can then be precisely measured.

For instance, if a grating with 1000 lines per inch (39.37 L/mm) travels 0.5 inch (12.7mm) past a point, then 500 interference bands would be counted.

The photo-sensitive devices enable the conversion of the light intensities into electrical signals of equivalent intensity. These waveforms are then used to produce a digital measuring system of two pulses per line of grating.

The direction of travel can be determined by inspecting two points on the fringe pattern. As illustrated in Figure 5.1(c), these are separated by an odd number of quarter wavelengths of the pattern. Their outputs make up a two-phase electrical system from which information on direction can be deduced.

The overall resolution of this novel diffraction grating measurement system is entirely dependent on the number of lines per inch (mm) on the gratings. Thus, for example, gratings with 500, 2500 and 5000 lines to one inch (25mm) would give rise to measurements to the respective resolutions of 0.001 in (0.0025mm), 0.0002 inch (0.0050mm), 0.0001 inch (0.00025mm).

This measurement system was free from the effects of either friction or wear; extraneous effects such as dust were negligible due to the large area of the photocell detectors relative to the size of a dust particle.

A positioning table was designed to use the system. It was equipped with two sets of gratings - each with an appropriate line structure.

In summary, a length of grating was fixed to the machine table, and another length of the same grating was attached to the slide. One grating traversed the other, with a typical gap between them of 0.004 inch (0.1mm). A beam of parallel light was sent through the pair of gratings. If they were suitably aligned, a Moiré fringe pattern would be produced. If there was relative movement, the fringe pattern would modulate the light intensity. One complete cycle of variation of intensity would occur for a movement equal to the pitch of the grating. By arranging the photocells so that the phase of this light variation was different in each, a two-phase electrical system could be produced. The total number of cycles represented the distance moved. The velocity of movement was given by the frequency. The direction of movement of the slide was represented by the direction of phase rotation. From this system, two or more discrete electrical pulses per grating line could be obtained.

Firstly, the workpiece was located with reference to the positioning table. A datum point was thereby established. Other points on the workpiece could then be defined in terms of linear displacements in two directions, at right angles to each other from the datum position. When the table was moved to the position, the sets of counters would display the appropriate figures.

Application of the system in linear or co-ordinate measurement could be controlled in three ways:

(i) Manual control, in which the movement was performed by lead screws. Decimal visual displays would indicate that the desired position had been achieved.

(ii) In pre-set control, servo-motors were used to provide power in each direction, usually by means of lead or ball screws. The amount of movement in each direction was pre-set on rotary switches for each position. The servo-motors drove the table until the pre-set displacement had been achieved. The movement was then automatically stopped. Any subsequent displacement from the correct position would be adjusted by the control equipment.

A series of positions could also be programmed on magnetic or paper tape. These positions were then adopted without the need for any manual intervention. Other procedures, for example, hole-drilling, could also be fitted into the programs, and controlled by the same information source.

Chapter Six: Patents, Presentations and Applications

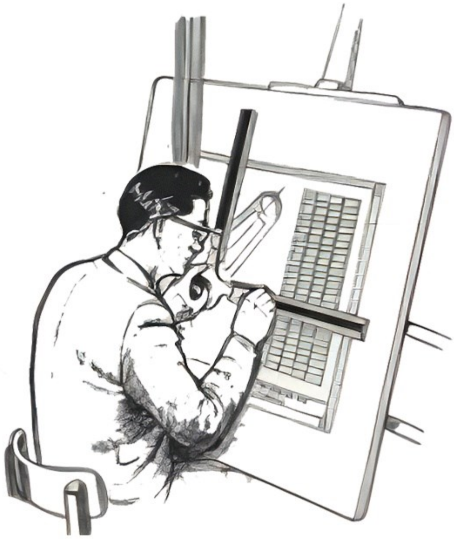
6.1 Patents

Patents were duly filed to protect the work that Williamson's group had developed. An estimated total of 23 British and 60 foreign patent applications were made, of which 9 and 17, respectively, were duly granted (Price, (1992), Feilden, (1992)). This enabled Williamson to describe their achievements in engineering journals (Williamson, (1954)) and at major events in the UK. He attended and presented papers at an Institution of Production Engineers Conference in Margate on the "Automatic Factory" in May 1955 (Williamson, (1955)) and at the British Association meeting in September of the following year, where a huge attendance listened to papers on automation including that by Williamson. (Williamson, (1956)).

At these meetings, he reviewed the steps they had taken to achieve computer-controlled machining, now known as the "Ferranti" system.

Although details of these steps have been presented in the earlier chapters, for continuity, a further summary is included below to augment how Williamson's team transferred their investigations into the industry as practice. Figure 6.1 (a) to (e) shows the sequence of events.

6.2 Ferranti System of Computer-Controlled Machining

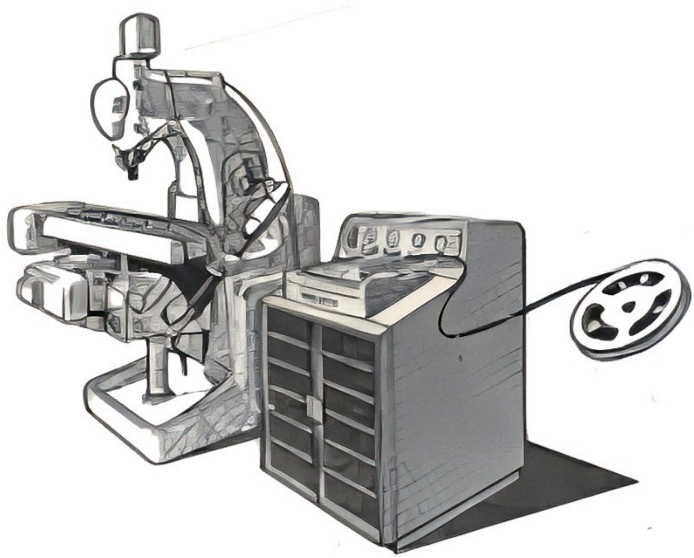


(a) Drawing dimensioned in a form suitable for system.

(b) Planning sheet from drawing.

(c) Conversion of information on planning sheet into form, used as input to the computer, transferred to magnetic tape.

(d) Computing operation to prepare magnetic control tape.



(e) Use of the magnetic tape in control equipment of the tool to determine continuous movements of each axis.

Figure 6.1 Ferranti System for Computer-aided Machining (based on information supplied by Ferranti)

Firstly, the part to be made was drawn and designed in the traditional way, except that it was dimensioned such that the information it provided was suitable for application by computer. All the dimensions of the part were given from a datum. The coordinates of all points of change were included, for example, where a straight line was joined by a radius.

With the drawing duly prepared, it was passed to the planning stage. The planning engineer would draw on his knowledge of the capabilities of the machine tool to be employed for that purpose and the way in which the part was to be machined. He put this co-ordinate information in the correct order in a planning sheet. At the appropriate stages, information would be added by the planning engineer using his own experience, such as the radius of the cutter, feed-rate, and rotational-speeds. Williamson used a simple example of the dimensioning and planning procedures, illustrated in Figure 6.2, for the machining of a two-dimensional cam.

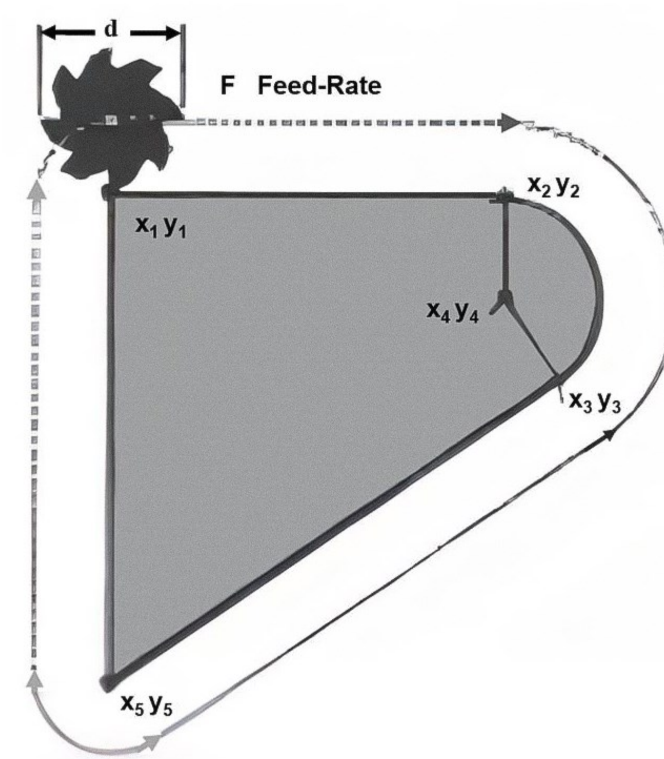


Figure 6.2 Dimensioning and Planning for Machining Cam

The planning sheet for the cam is shown in Table 6.1.

Type of Curve	Co-ordinates of change points	Co-ordinates of pole of curve
LINE	X_2Y_2	
CIRCLE	$X_3\,y_3$	$X_4\,Y_4$
LINE	$X_5\,Y_5$	
LINE	$X_1\,Y_1$	

Cutter diameter = d. Feed-rate = F. Co-ordinates of datum ($X_1\,Y_1$)
Note d and F specified in program.

Table 6.1 Planning Sheet for Machining Cam (after Williamson (1968)

With this approach, no co-ordinate information had to be supplied between points. That information would be specified by an equation or parameters of a curve, e.g. circle, ellipse, parabola. This procedure could readily be applied to computer-aided machining for three-dimensional components, using *x, y, z* coordinates, the "digital differential analyser" (DDA) being used. The planning sheet with these data was then transferred via a teleprinter onto punched paper or latterly, magnetic tape.

With the DDA, the computer would be used to calculate the path of the centre of the cutting tool in three-dimensional, *x, y, z* coordinates. The calculations for each coordinate would take the form of an output in the form of a series of pulses. Each of the pulses was equivalent to a very small movement – typically about one ten-thousandth of an inch (0.0025mm). The total number of pulses in each channel determined the distance travelled for that coordinate. The rate of transmitted pulses, in effect, defined a tool-speed, i.e. its feed-rate.

The pulses were synchronised in three x, y, z channels, such that they directed the path taken by the tool. Its track aligned with the computed one, given by the pulses, to an accuracy of better than 0.0001 inch (0.0025 mm).

As well as the pulses being coordinated to enable the tool to follow an accurate path, they were synchronised in the x, y, and z planes. Three-dimensional shapes could then be machined. Contours could be machined in any shape: circles, ellipses, parabolae and hyperbolae. Other profiles could be produced to a close approximation by any combination of these shapes.

In traditional machining methods, the machine operator would be given a dimensioned drawing of the article to be made. He would then adjust the machine so that it performed the operation specified. At requisite stages, he would have to check that the operation was proceeding correctly to confirm that the desired result had been obtained. The process required skilled and experienced machinists. Williamson and his team had changed this approach. He observed that they were not aware of any other comparable work elsewhere, and so were able to work from first principles. They had drawn on the characteristics of a typical machine tool, such as a milling machine, which has a table that can provide horizontal motion. Its cutter head can move in both vertical directions (up and down), and in a cross-slide in a horizontal direction to the table. In this way, the cutting tool and workpiece could make contact at any point in space within the range of the machine tool. The cutting head could also be provided with rotation about two axes at right angles to the spindle and to each other. The motion of the cutting tool in relation to the workpiece could be specified by means of the coordinates of the points through which the cutting tool had to pass.

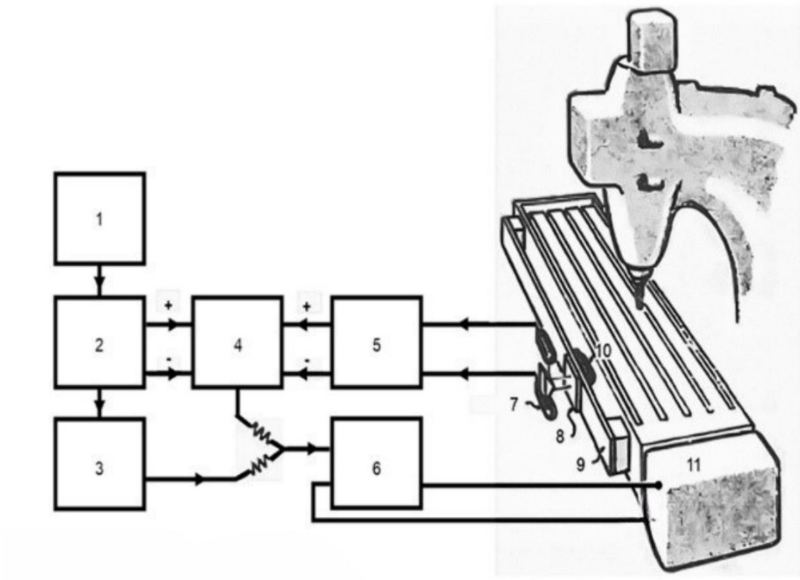
The Ferranti group had to take into account possible errors in the compilation of the data to be coded on the paper tape, the very coding, the reading of the paper tape (eventually replaced by the magnetic tape) and the entire computerised process, and everyday human error. Such checks in the system were performed before the machining stage was reached. Techniques used at that time in accounting systems were adopted. Essentially, this consisted of duplicating the work and comparing the results.

Many of these advances depended on the advantages of magnetic over paper tape. Pulses could be recorded on magnetic tape at a much faster rate than was possible with punched paper. Machining information was fed to the computer, which was capable of rapidly processing it and implementing the required operating settings.

As a final check on the computer-controlled machining operation, a "closed loop" approach was adopted. This procedure consisted of instructing the tool to touch its previous path on several occasions during machining. This was always possible, even though the tool would be lifted away from the workpiece when no cutting was needed. At the point at which the loop should be closed, a "marker" pulse was placed on the magnetic tape. After recording, the pulses on the x, y, z channels were counted immediately. If the "summate" was zero at these points, the tape was concluded to have the right data recorded on it, and accurate machining could be expected.

6.3 Digital Machine Tool Servomechanism Operation

Figure 6.3 illustrates how the pulse trains from the magnetic tape reader were used to yield accurate slide movements.



1: Four-Channal Magnetic Tape Equipment
2: Direction Interpreter
3: Rate Meter
4: Register Reversible Counter
5: Direction Discriminator
6: Magnetic Amplifier
7: Photocells
8: Fixed Grating
9: Moving Grating
10: Light Sensor
11: Motor Tachometer

Figure 6.3 Machine Tool Servomechanism (by permission of the Institution of Mechanical Engineers)

A servomechanism was employed for this purpose. As an example, for one channel in Figure 6.3, the control pulses were fed to a “direction interpreter”. They then went to a reversible counter “register”. The register had an electrical output that was proportional to the magnitude and direction of its contents. The control pulse train was also transferred to a “rate-meter”. The electrical output from the rate-meter was proportional to both its repetition frequency and direction. These two outputs, when combined, activated a secondary servomechanism. This servomechanism drove the table. As indicated in Figure 6.3, a grating and direction discriminator gave positional feedback from the table. Pulses from the discriminator were used to cancel the command pulses in the register. Error between the command pulses and the positional feedback from the table did not exceed one pulse. That meant that the maximum error in the slide position was only half a grating line (a quarter of the grating pitch).

6.4 Safety and Reliability

Williamson’s team also sought to anticipate the effect of errors should the servomechanism be inadvertently overloaded. They ensured that the computer could limit the maximum rate of change of command information in order to ensure safe handling.

Indeed, safety and reliability were key. The risk of failure was reduced through the circuit design and the use of mainly carbon resistors and germanium diodes. Automatic self-checking procedures were performed. Daily testing was undertaken with reduced supply voltages - whilst the checking was being performed.

In the event of unexpected failure, spare plug-in circuit boards enabled prompt replacement of faulty parts whilst appropriate remedies were being taken.

The Ferranti group also prepared for the occurrence of a fault in the control region. The machine would cease operations immediately so that the workpiece would not be damaged: the signals from the register indicated the deviations between the required and actual position of the slides. These signals were arranged such that if the deviation was greater than a specified pre-determined limit, the machine would be shut down. This arrangement, together with two "anti-coincidence" counters that covered the channels from the tape to the register, and from the grating to the register, ensured that the machine performance was fully monitored throughout machining. The appropriate accuracies of +/- 0.0005 inches (0.0127mm) were now readily obtainable.

6.5 Optical Grating Measurement

The measurement system has been described in detail above. In summary, diffraction gratings were used for accurate control of the table movement. As shown in Figure 6.3, a strip of grating was fixed to the machine slide. A second section of the same grating was attached to the slideway: one grating traversed the other, the two surfaces almost contacting one another.

A beam of parallel light was transmitted through the set of gratings. If they had appropriate alignment on their relative movement, a (Moiré) fringe pattern would be generated, which would modulate the light transmission.

The system provided an indication of the distance, velocity and direction of movement of the slideway. Its arrangement meant that the maximum error in movement would be 0.0001 inch (0.00254 mm).

6.6 Errors in Machining

Machining errors were known to emanate from the inherent characteristics of the machine tool and by deflections and deformations arising from stresses during cutting, such as elastic deformation; the latter could be as much as 0.001 inches (0.0254mm). In conventional milling, such exigencies are catered for by using roughing and finishing cuts. This procedure was adopted in their development of computer-aided milling. The paper tape program was run through the computer twice. Firstly, a value was selected for cutter diameter that was, for instance, 0.010 inches (0.254mm) greater than that to be used. In the second run, a cutter diameter value was used that differed from the actual amount by a quantity that was sufficient to cater for the expected elastic deformation, as found from the earlier run.

Other errors from the machine tool were also considered, such as backlash in the drive, friction, and slide inaccuracies. To cope with backlash, the computer was programmed such that when reversal of the slide was needed, one pulse went automatically in the reverse direction. The computer would then pause momentarily, during which time the servomechanism would cancel this pulse. Then it would continue with the rest of the train of pulses.

The power needed for the servomechanism to overcome the inherent inefficiencies of about 15-20 per cent in the slide and drive systems was also taken into account. Conventional leadscrews and the consequential problems that they could bring in computer-aided machining saw these devices being replaced by re-circulating ball nut pairs. These were fitted with special lead screws that were pre-loaded to the highest likely table force of 500 lb (2.227kN). The transmission efficiency, which had stood at about 20 per cent, now rose to 80 per cent.

As well as high efficiency, these developments removed problems in maintenance, they would supply the rigidity needed for the machine tools, and reduced backlash to less than 0.0001 inch (0.0025mm). With these innovations, there was also no deterioration in accuracy due to wear.

Although the effort was directed towards computer-aided milling, they also saw the associated grating measurement system had other applications; for example, it was also used in ‘inspection machines’ or CMMs (Coordinate Measurement Machines) to measure and check components after machining.

In particular, its relevance for drilling machines, jig borers, and automatic lathes, in which the table only needed to be positioned without having to cut out a profile, was also possible. The procedure could be set up manually or automatically by use of a punched card or paper tape. These methods could lead to consistent accuracy and high rates of cutting when, for example, the drilling of a pattern of holes had to be performed. An automatic drilling machine of this type is shown in Figure 6.4.

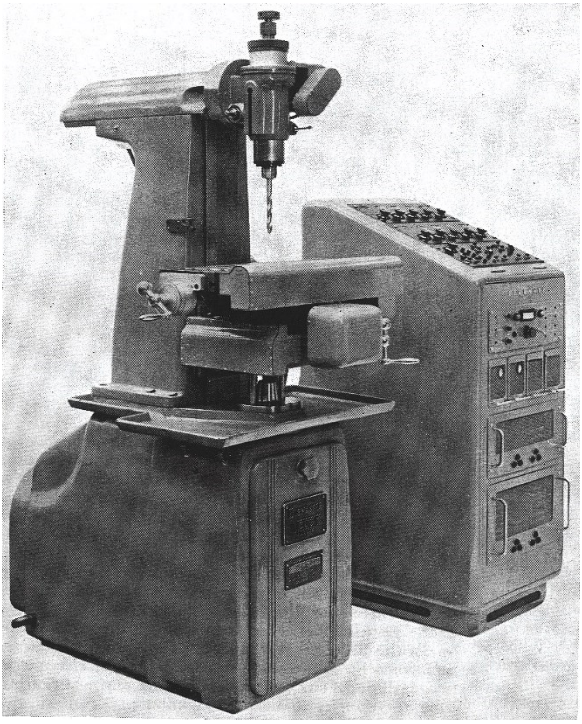


Figure 6.4 Automatic Setting Co-ordinate Drilling Machine (by permission of the Institution of Mechanical Engineers)

6.7 Applications

The Ferranti team was now in a strong position to investigate applications for their new system, for which some case studies are described below. But before applying their breakthrough, the team was encouraged to consider the economics of their novel computer-aided machining system.

6.8 Economics of Computer-Aided Machining

Williamson and his colleagues looked to evaluate the economic attraction of computer-aided machining. The machining of cams was considered, as discussed earlier. Traditional methods for making a three-dimensional cam for a turbine blade miller would need about three weeks. The entire computer-aided methods required four hours, without any requirement for manual finishing.

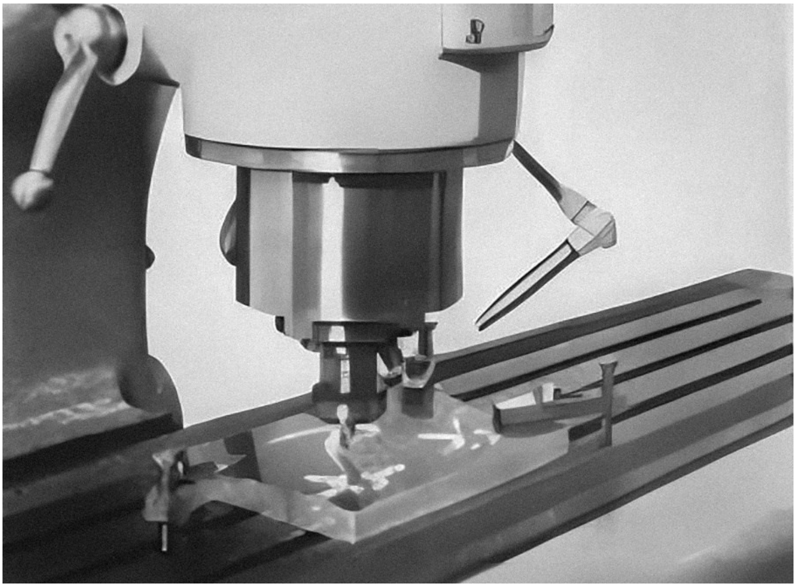


Figure 6.5 Computer-Controlled Machining on Milled-Block Waveguide (by permission of the Institution of Mechanical Engineers)

Another example shown in Figure 6.5 was even more impressive. A conventional vertical milling machine with a rotating head was used to produce a block waveguide structure which possessed a very accurate track in a light (aluminium) alloy; a mirror image of the track was machined in another block. The two parts, when placed together, formed a complete waveguide assembly. The entire machining took two weeks. By computer-aided milling, both halves could be made in one hour, and the use of a high-speed routing head could further reduce the machining time to ten minutes.

6.9 Fairey-Ferranti Milling Machine

Fairey-Engineering, through its managing director, Alan Vines, John (later Lord) Gregson, then its chief designer, and co-designer Alex Flett, worked with Williamson's Ferranti team to design and build a vertical milling machine, about 3m by 10m, aimed at milling aircraft wings.

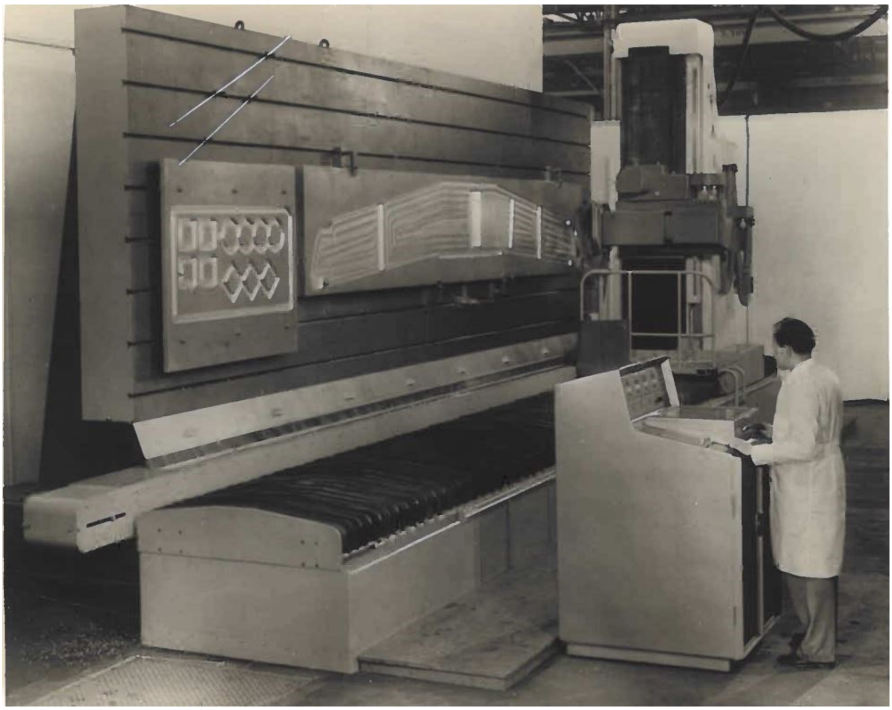


Figure 6.6 Fairey-Ferranti Milling Machine (by permission requested from Keystone Press Agency)

Its slideways possessed innovative hydrostatic bearings; the machine was fitted with hydraulic servomechanisms using aircraft hydraulic motors that had been designed by Vickers and electro-hydraulic control valves.

The column of the machine tool had a hydraulically-driven cutting head that could operate at speeds as high as 8000rpm with about 50hp

(36.8 kW). The rate of metal removal was so high that all the heat produced by cutting was retained in the swarf and chips, with little heat being transferred to the workpiece. Thus, the shape of the component and its dimensions remained unchanged by the “adiabatic” machining.

Despite the 5-ton (4536 kg) weight of the column, the friction was so low that it could be pushed manually with little effort along the slideways.

The Fairey-Ferranti milling machine was ready for use by 1957. It was employed to make the tail engine cowlings for the Trident aircraft, and later for the sections of the ramps that were used for launching the Sea Harrier from aircraft carriers. It was regarded as the most mechanically perfect machine tool that the teams from the two companies had ever produced.

The Ministry of Supply supported the development and proudly exhibited the machine tool in London, from which the photograph in Figure 6.6 was taken.

6.10 Cams for Cigarette Machine

Ferranti was approached by Ted Broome, managing director of London-based Molins Machine Co. Ltd, for collaboration in the design and manufacture of a machine tool to make three-dimensional cams needed for their patented flip-top cigarette packaging machinery. Molins sent its staff draughtsmen to Edinburgh, where the structure of the machine was worked out and designed. Williamson and his colleagues prepared the servomechanisms, controls and software.

A machine tool that entirely served the purposes of the London company was built, and indeed, a second one was duly commissioned to increase capacity.

Williamson was invited by Ted Broome to join Molins as Director of Research and Development, with a seat on its board. The salary would be about four times that of his present pay – which Ferranti could never equal – and more than that of the Prime Minister. Several visits were made to see the company in London to discuss what they wanted of him. By this time, Williamson was married with three young children, and the salary alone was attractive, in addition to the exciting technological challenges of the job.

Williamson accepted the offer and, with the goodwill of his colleagues, left Ferranti in February 1961.

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Chapter Seven:
Molins Machine Co. Ltd., London

7.1 Introduction

The two Molins brothers, Walter, an engineer, and Harold, a businessman, founded the company about 1912. Walter Molins (Figure 7.1) invented a machine for manufacturing paper packets in which five Woodbine cigarettes could be held. Their prototype machine came to the attention of the cigarette company, W D and H O Wills, who ordered about twenty of the machines, financing their manufacture by lending the capital needed to Molins.

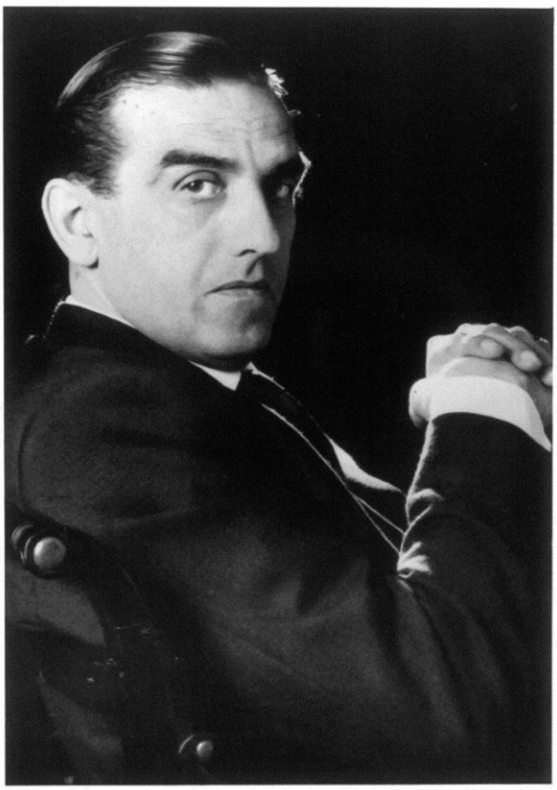


Figure 7.1 D. Walter Molins, O.B.E., Owner of Molins

In return, Wills were given a substantial equity holding in the company. Thus began Molins' work with the cigarette industry, and Walter duly proceeded to develop other types of packaging and machines for actually making cigarettes. Towards the end of the 1930s, Molins' business was entirely taken up with work related to tobacco.

During the Second World War, the firm had to use its facilities and expertise for the benefit of the war effort. Walter Molins' son, Desmond, for example, worked on equipment to be used by Anti-Aircraft Command, while colleagues at Molins developed ammunition-feed mechanisms for 20mm cannons in fighter aircraft and the design and construction of machines for cutting and packaging the aluminium foil used in "Window", which the RAF used on D-Day, dropping the foil in order to confuse the enemy radar and divert enemy defences away from the Allied landing sites.

Following the end of the War, Molins returned to its work on tobacco machinery. It had captured two-thirds of the international market in this sector and, by 1960, was exporting 78 per cent of tobacco machines. (Nonetheless, about this time, strong competition in this market was also starting to emerge, especially from German companies).

7.2 Mark 8 Cigarette Machine

Molins had bought the design of its "Mark 8" cigarette-making machine from the French firm of Decouflé and had employed its inventor, Francis Labbé, as a consultant.

The Molins Mark 8 was the market leader and made 1800 cigarettes per minute. The cigarettes were loaded into tray fillers, which were manually handled between the “making” and “packing” machines, as they worked at different speeds. The relative numbers of makers and packers could be adjusted so that output could, on average, equal consumption.

The flow of tobacco, just before it was wrapped, was monitored electronically by use of Beta radiation from a Caesium 137 source. This enabled measurement of the particle count through the cigarette rod and then activation of a mechanical trimming device so that the weight of the rod could be maintained consistently to less than one per cent. By this method, cigarettes were neatly, but not overly, packed, and this was an attractive and economically beneficial feature of the Mark 8 machine.

On the other hand, the Molins Mark 8 cigarette machine could be unreliable. The principle of the machine was based on handling tobacco by means of ducted compressed air. The system would run steadily, and then suddenly, choking would occur due to the intrinsic properties of the tobacco, which varied according to its source.

The engineering problems associated with mainly the Mark 8, but also with other products, had to be tackled by Williamson on his arrival. To address them, he needed good mechanical and electronic engineers.

He first recruited E.G. (Ted) Preston from the English Electric-owned firm Napier, who became his Chief Mechanical Engineer. D.W. Muir, formerly of Ferranti, became the Chief Electronics Engineer. With their expertise and that of others, the design and of Mark 8 machines significantly improved.

Until the arrival of Williamson, Molins had most of the components they needed made by machining from metal castings. He recruited a materials engineer, Clive Perkins, who, with some colleagues, selected the appropriate materials for a range of specific applications. In particular, plastics were identified as a material that could replace many of the costly metals that Molins had traditionally used.

Glass-filled nylon and other reinforced plastics were concluded to be effective replacements and would let them make other mechanisms which could not be readily produced from metal. Short-run trials with a small injection moulding tool, with brass moulds, convinced them of the value of this new approach.

An experienced, practically-minded plastics engineer, Don Barber, was recruited from the S.T.C. company, along with his moulding machine operator and tool designer, Harry Dobbs. Two top-quality injection moulding machines were bought for them. They made their own moulds, usually in brass, and soon, they were making more parts in plastic in place of metal. This transition drastically changed the approach to design at Molins, where the economic and practical benefits of materials other than metal had previously not been properly considered.

7.3 Design of Cigarette Machines

These, and other improvements in design, were at the heart of Williamson's Molins team as they sought to increase the speed at which the Mark 8 machine produced cigarettes. Over the next ten years, the speed rose from 1800 to 8000 cigarettes per minute. An early version of the Molins Mark 8 machine is shown in Figure 7.2. Its successor, the Mark 9, was built for the latter purpose and at little additional expense compared to the Mark 8, as the cost of manufacturing and materials was hardly different. The added value thus became much higher – a considerable attraction for the companies buying the Molins machines.

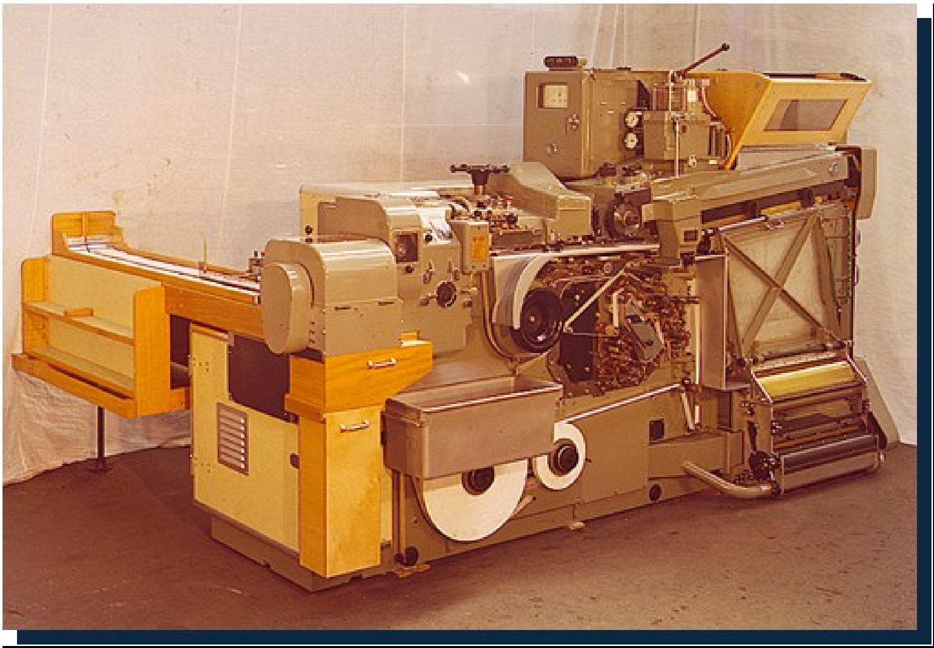


Figure 7.2 Molins Mark 8 Cigarette-Making Machine (Courtesy of Molins)

With these improvements in the speed of the Mark 9 machine, they turned their attention to the design of the packing machines. As the speed of making cigarettes rose, the handling between them and the packing machines became more and more inefficient. The latter carried many intermittent mechanisms. The new designs were based instead on continuous flow mechanisms. Cigarette flow was regarded as a fluid between the makers and packers. Between them, the design incorporated mechanisms to accommodate variations in the flow when individual machines had to be stopped and then re-started.

Over the next ten years, with considerable effort, the new continuous flow package machine systems were developed.

The Molins cigarette-making and packaging machine product line was completely revolutionised with these changes.

With machine speeds increased, the application of electronics to the tobacco machinery was the next target. As noted above, its sole use in 1961 was the electronic measurement of the weight of the cigarette rod by Beta radiation. Now, with filter-tipped cigarettes the fashion, problems such as leaking of the filter-tip attachment were resolved by electronic detection and correction. Electronics became the mainstay of the manufacture and operation of the Molins machines.

Other companies had now started coming to Molins for technical support. For example, Williamson's team was able to solve the problem of maintaining the sharpness of the razor strip for a major manufacturer of safety razors.

On Williamson's recommendation, Molins also procured a Hayes numerically-controlled (NC) milling machine to investigate which parts, other than cams, could be made by this technique. The machine was very quickly in great demand: the geometry of many of the components needed, especially for the packing machines, were ideally suitable for NC machining.

7.4 Twin-Spindle Milling Machine (TSM)

His experience with Molins' cigarette machines led Williamson to the conclusion that numerically-controlled machines could lower manufacturing costs for Molins. About 70 per cent of the parts needed for their machines fell within 300 by 150mm in size, and 80 to 90 per cent of the metallic ones could be produced from light alloy.

In less than 12 months, a novel twin-spindle milling machine was duly designed and constructed to serve this purpose. A spindle power of approximately 20hp (14.9 kW) at speeds as high as 30000 rev/min was required. Williamson and his team made a small Pelton wheel spindle, which was driven at constant temperature by a high-pressure oil jet, the speed and power of which was servo-controlled by a needle valve. The waste heat generated by the spindle movement was thereby removed by the oil.

Hydrostatic slideways were used for the twin-spindle milling machine; they combined the hydraulic actuator with the slideway in a cylindrical form, which could be readily and repeatedly manufactured to high accuracy by precision grinding. Each was complemented by a single flat hydrostatic slideway to give a kinematic pair. A Molins Twin-Spindle Milling Machine is shown in Figure 7.3. Molins now had an entirely new way of rapidly making the light alloy parts needed for their machines, and at a low cost. The machine was numerically controlled; it was small in size and had very high metal removal rates enabled by using a fast cutter spindle combined with rapid slideway movements. Figure 7.4 shows one hour's output each from a twin-spindle milling machine.

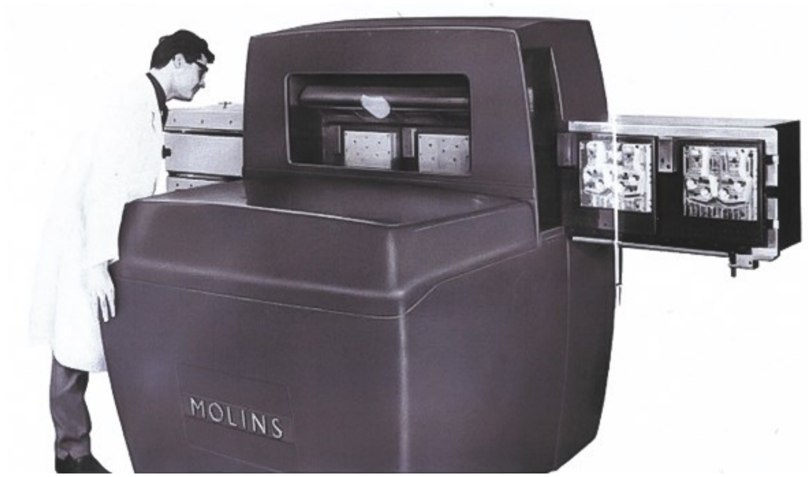
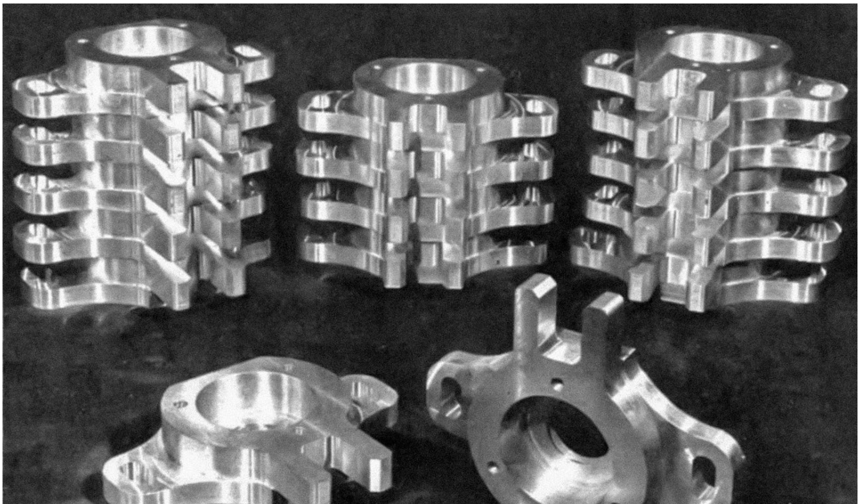
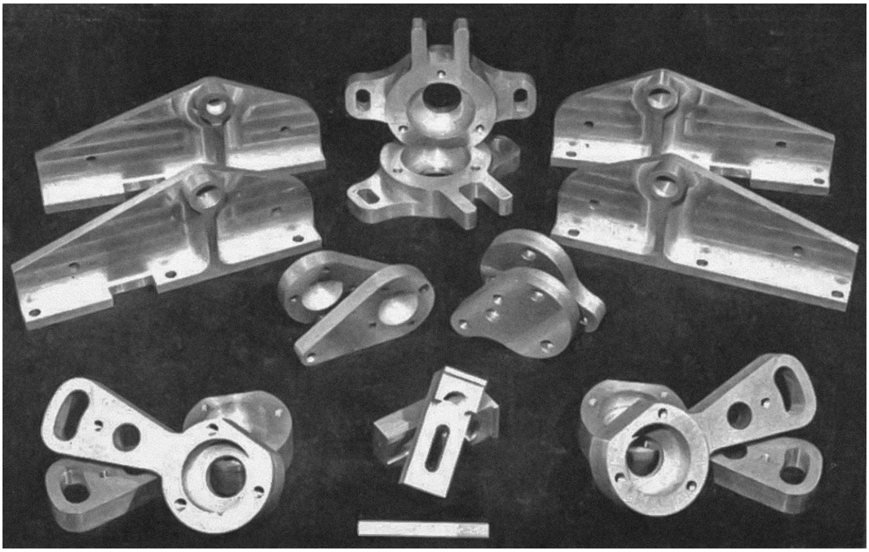


Figure 7.3 Molins Twin-Spindle Milling Machine (TSM)



(a)



(b)

Figure 7.4 (a), (b) One hour's output each from a Twin-Spindle Milling Machine (by permission of the Institution of Mechanical Engineers)

These twin-spindle, high-speed machine (TSM) units, whilst serving Molins' cigarette business well, had applications elsewhere. About 15-20 TSMs were made; two, for example, were bought by Aérospatiale, France, for machining the window frames for the Concorde. The TSMs that were sold had many of their components made out of Molins as the specifications could not be met by the firm's manufacturing equipment at that time. Greater skill levels and air-conditioned clean-room facilities for assembly, especially for some hydraulic parts and bearings, were required if Molins were to move further into the manufacture of the TSMs. Nevertheless, Molins staff carried out the assembly, testing and commissioning of these TSMs. They were produced in a specially designated building at Saunderton, near High Wycombe, where the cigarette-making machines were located.

The TSMs provided Molins with a ready means of moving into markets beyond cigarettes. Although the fashionable filter-tipped cigarettes and new shapes for cigarette packs were opportunities that the company's novel machine tools could readily meet, misgivings were starting to emerge even then about health concerns related to cigarettes. Furthermore, the added value of the TSMs themselves was far greater than that of the Molins' tobacco and cigarette machines or of paper-making equipment, another area into which the firm was considering diversifying.

The TSM gave rise to the concept of an integrated automatic flexible manufacturing system (FMS), the design of which proceeded over the following four to five years. In that time, two machines were developed and produced for an estimated cost of £ 50,000. The FMS was named "SYSTEM 24". The "SYSTEM 24" could be operated for 24 hours; it was fully manned for one shift, with only maintenance staff being needed for the two other shifts. A component, fixed to an accurately locatable pallet, could be transferred to a set of complementary machines that provided any type of machining that was required and incorporated automatic clearance of chips and swarf.

Williamson had earlier appointed a young and talented industrial designer with a view to improving the appearance and ergonomics of the tobacco machinery. He now directed him to look at the design of the machine tools, their appearance, their ease of manufacture, and how to incorporate the provision for all the automatic material and tool transfer systems. The design should capture the essence of a fully automatic system. Molins also had a very good model maker who had made scale models of most of the tobacco machinery. He made a model for Williamson of the entire SYSTEM 24. The model was very impressive and encapsulated every aspect: storage racks, machine tools, buffer stores, workpiece loading and unloading stations. It demonstrated very clearly how SYSTEM 24 worked and, moreover, what it could be capable of achieving.

A report on SYSTEM 24 was submitted to the Board of Molins. It was decided to construct a new building, the "D S M Building", after the initials of the Chairman, next to the main works, in Trundleys Road, Deptford. With the architect, Williamson designed the building to house the entire seven-machine system. An underground powerhouse would be used to take the hydraulic machinery that was noisy. Swarf and its baling would also be gathered in this area; it would be re-melted and could be re-used as a pre-form material (a 1960s example of current recycling practice). A hall on the ground floor housed the complete mechanical system. The ceiling was made from sound-absorbent materials, and suitable heating and ventilation equipment was installed. This manufacturing environment was very different from that of Molins' other production areas. Workpiece preparation and tool areas were sited next to the machine hall; here, cutters could be re-grounded, and fixturing prepared for different parts as required. A mezzanine floor above the hall was used for the computer and for the part-programming needed. Adjacent to this part of the floor was a viewing gallery. From here, visitors could see the entire system at work, as presented in Figure 7.5.

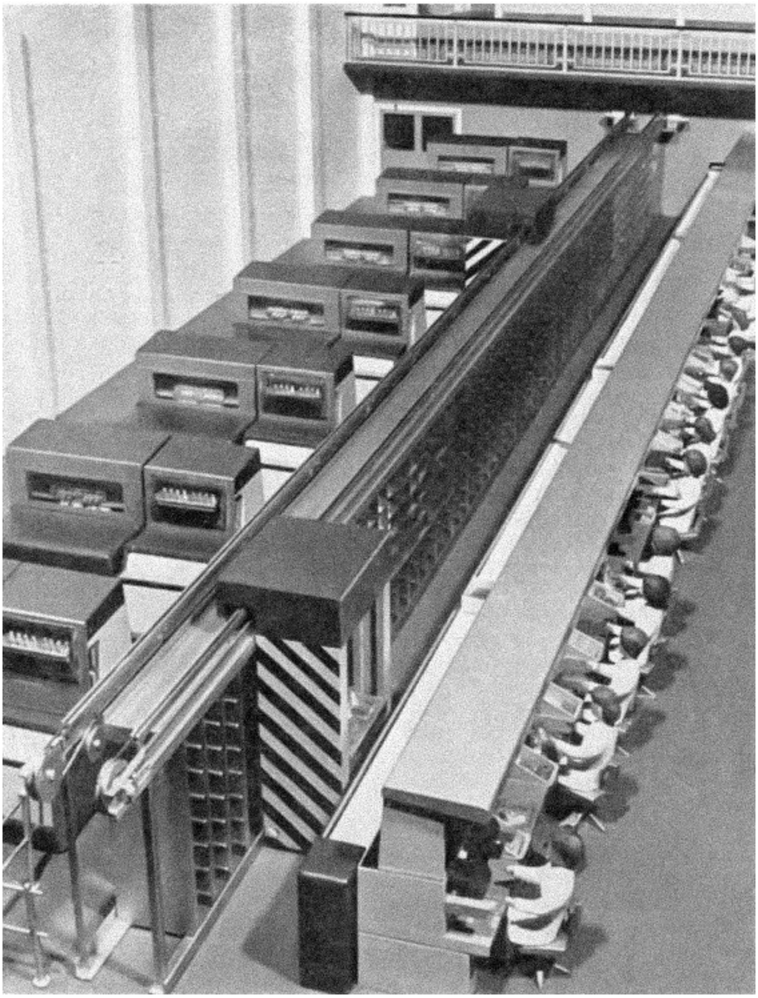


Figure 7.5 Model of the first SYSTEM 24 installation at Deptford (by permission of the Institution of Mechanical Engineers)

Chapter Eight: Flexible Manufacturing Systems (FMS) (SYSTEM 24)

8.1 Technical Concept

In a keynote address to the 8th International Machine Tool Design and Research Conference (MTDR) at the University of Manchester in 1967 and in the James Clayton Lecture at the Institution of Mechanical Engineers (IMechE) the following year, Williamson presented the new system of manufacture developed at Molins. (Williamson, (1967), (1968)).

In both lectures, he first summarised the methods of batch production and then in existence. Up to that point, improvements in tools and tooling, and, less so, in organisation, had taken place over centuries.

Batch manufacture was undertaken with work divided into individual operations. The part to be produced would first be worked on by one machine or undergo some process, then be transferred to another machine or process for the next stage in its production. As a result, factories would consist of lines of milling machines, lathes, drilling machines and so on, with parts stacked between the lines. With this kind of organisation, manufacturing errors could often only be spotted in the final stages.

Williamson pointed out that this approach, coupled with an increasing lack of skilled machine operators, had given rise to the need for an entirely new approach to batch manufacture.

He argued that the present organisation of batch manufacturing should be entirely replaced by a new system of design and manufacturing so as to make far better use of operator skills and equipment. The need for drastic improvement was urgent due to an ever-increasing demand for parts of higher quality, performance and longer lifetime.

Williamson recognised that the limitations of traditional single-unit (amorphous) organisation, as described above, had been addressed by the introduction of "cell manufacture". Here, machine tools and their operators were gathered into "cells" for the production of components of one type or ones of great similarity. Cell manufacture could deliver an order of magnitude decrease in batch manufacture cost, as indicated in Table 8.1, which also shows other benefits of cellular over amorphous organisation.

		Amorphous arrangement	Cell arrangement
1	Capital investment/unit output	High	Lower
2	Labour cost (incentives and rewards) . . .	Similar	
3	Preparation and supervision cost	High	Low
4	Inspection cost . .	High	Low
5	Inventory cost (stocks and work in progress) . .	High	One-fifth
6	Space	High	Lower due to lower stocks
7	Speed (cycle time for part manufacturing) . .	100	10–15
8	Use of available skill .	Poor	Good
9	Communication . .	Poor	Excellent
10	Machine tool loading .	Good	Probably less good
11	Discipline and team spirit .	Poor	Excellent
12	Ease of control . .	Difficult	Easy
13	Minimizing waste . .	Difficult	Easier
14	Material flow . . .	Costly	Simple
15	Accuracy of costing . .	Must be averaged	Precise

Table 8.1 Comparison between "Amorphous" and "Cellular" Systems (by permission of the Institution of Mechanical Engineers)

From Table 8.1, Williamson emphasised the current requirement for appropriate "communication", i.e., for the transfer of information as to how a component was to be made, either verbally or through documentation such as drawings. There was also a need for the machine operator to have sufficient know-how, usually gained through experience. He pointed out that much of the necessary knowledge and capability for its successful communication lay in the staff of a company; people would leave or retire and were not always replaced, reducing the number of skilled operators. The range and complexity of components to be produced were increasing and, with a decline in the number of staff with the required knowledge, this meant that “cell”, although better than “amorphous” manufacture, was still not the solution.

These deficiencies led him to discuss approaches based on the classification of parts by their shape for the design and grouping of machine tools or “multi-cellular” organisation. The associated “group technology”, in vogue at that time, could use part-numbering for classification for manufacture.

Williamson doubted whether classification by geometrical shape was the right way forward and, whilst classification by part-number could be better, it had its drawbacks when the workflow was computer-controlled.

Instead, he recommended “functional classification”. Here, a part would be allocated a simple serial number and then a two-digit classification. All the other information needed about the part would be stored in the computer, under that number. Table 8.2 is a typical example of how components could be classified.

Its benefits were seven-fold.

(1) Parts were grouped logically with their final use in completed equipment.

(2) A similar set of materials was employed by the manufacturer for parts in a specified group.

(3) Parts in any one group would usually possess similar working conditions, such as wear and fatigue.

(4) Experience and "know-how" on the machining needed would be concentrated within a cell.

(5) There would be a considerable operational benefit from knowing that the machining of a particular group of parts could be tackled within the cell.

(6) Parts found on assembly to have faults and errors could be more readily fixed through communication between the cell and assembly heads.

(7) The main outcome from these measures was far better communication.

01	Transmission items: gears, sprockets, timing belt pulleys, ratchets
02	Cams
03	Shafts
04	Mainly turned parts
05	Covers and light structural parts and mainly fabricated items, formed sheet metal items
06	Fasteners and associated 'indent' type items
07	Levers, cranks and connecting rods
08	Brackets
09	Milled parts with holes
10	Gearbox housings
11	Beds and large structural members
*12	Hydraulic manifolds and valves
*13	Rods and hydrostatic bearings
*14	Machine tool structural castings
†15	Fluted drums
†16	Garnitures and slideways
17	Parts of unusual or awkward nature
18	Plastic parts (injection moulded, cast or built/laid up)
19	Woodwork
20	Proprietary items bought complete
21	Cableforms and looms, wiring harnesses, electronic chassis
22	Etched and chemically machined items (including printed boards)
23	Electronic circuit cards
24	Electronic transducers

1–11 Basic mechanical engineering cells.
* Cells special to Molins machine tools.
† Cells special to Molins tobacco machinery.

Table 8.2 Functional Classification of Components (by permission of the Institution of Mechanical Engineers)

Williamson advocated that for the cellular structure to work effectively, no more than ten people should participate and preferably less – about six.

Fluctuations in load could be handled by computer scheduling. Dedicated software could be written to sort out particular problems and duly modified at any stage in the light of experience.

The cellular structure also permitted vastly improved utilisation of plant and the machine tools needed, and the costs for the use of plant, labour and overheads could now be much more precisely estimated.

It was this view of how batch manufacture could be improved by these changes in its structure that led him and his team at Molins to embark on SYSTEM 24.

The Molins work relied on three factors –

(a) The use of light (aluminium) alloy instead of ferrous alloy as a constructional material in manufacturing.

(b) The use of a multi-tool concept to replace the current practice of a single numerical control (NC) machine tool. He advocated that the former effectively was a flexible transfer line providing improved efficiency and flexibility.

(c) By (a) and (b), an entirely computer-controlled process could be used; automated decisions could be quickly made, thereby removing "dead" time arising from manual decision-making and handling of materials.

Within Molins, SYSTEM 24 was devised to lower the costs of manufacturing the components needed for the firm's equipment for making and packing cigarettes. About 30 machines were manufactured for this market sector, each of which had between 1000 and 3000 components. Above 70 per cent of these components had dimensions within approximately 300 x 300 x 150mm. They were mainly made from ferrous alloys and were machined from the solid or from castings, using hand-operated tools in the "amorphous" traditional process.

The cost of using numerical control instead of manual machining was difficult to justify due to the metal-removal rate achievable with ferrous alloys. This impediment was removed by the decision to use light alloy for about 80 to 90 per cent of the components needed for the cigarette machines.

Williamson's team now worked on providing a set of complementary machine tools, such that each machine in the group would perform its own manufacturing procedure. A component would be passed from one machine in the group to another, each performing its own specialised operation. In his James Clayton Lecture, Williamson gave the example of a component which first might require 50 per cent of its manufacturing time on a three-axis milling machine. Next, it might need 40 per cent on the production of holes, by, for example, boring, reaming, drilling and tapping, on an adjacent machine in the group, and the remaining 10 per cent of its manufacturing time for sculpturing a complex shape. Each of the machines involved would carry out these procedures at different speeds appropriate to the operation. For example, a three-axis milling machine would run at about four times the speed of its six-axis counterpart when high rates of metal removal were needed.

Grouping complementary machines so that a part could be readily transferred from one to another considerably enhanced the overall efficiency of the manufacturing process. Additionally, this open-ended system could be easily adapted if a further machine was needed.

Parts were transported on specially designed pallets of size 330 x 330 x 330mm. An accuracy of location to 0.0025mm on the worktables that carried them was maintained through the use of an electronic servo-location system.

The six-machine SYSTEM 24 was to produce 2000 to 20,000 components a day. An online computer system was designed to control the entire operation.

8.2 Integrated Batch Manufacturing System

Absolute computer control required consideration of every detail of manufacturing. Williamson summarised the need: how to deal with initial demand, materials preparation, work-fixing and their tooling, automatic transfer of materials and pallets, and machine tools where a computer-controlled every aspect of manufacture – from change of cutting tools, disposal of swarf, change of computer program, and re-setting of the workpieces, to unloading of the completed part and its handling, and transfer to mainstream manufacturing operation and assembly.

To meet all these needs, Molins decided to build their own machine tools. They would have the following features

(i) Small capacity (300 x 300 x 150mm)

(ii) Reliability for 24 hours, for which hydrostatic bearings would be needed.

(iii) A minimum of two simultaneous cutting spindles to provide the required increase in productivity.

(iv) A vertical or inverted ("upside-down") machining surface for chip and swarf clearance.

(v) Very high acceleration rates to meet the required speed of cutting.

(vi) High spindle horsepower (15-20 bhp (11.1kW-14.9kW)) at speeds of up to 30,000 rev/min for fast rates of metal removal.

As well as three-axis machines, a five or six-axis machine would also be needed.

The machine tools were constructed with novel hydrostatic slideway members, machined to extremely high accuracy. Additionally, all slideways featured hydraulic actuation. The moving parts of the slides were mainly made from light alloy to improve servo performance (Figure 8.1).

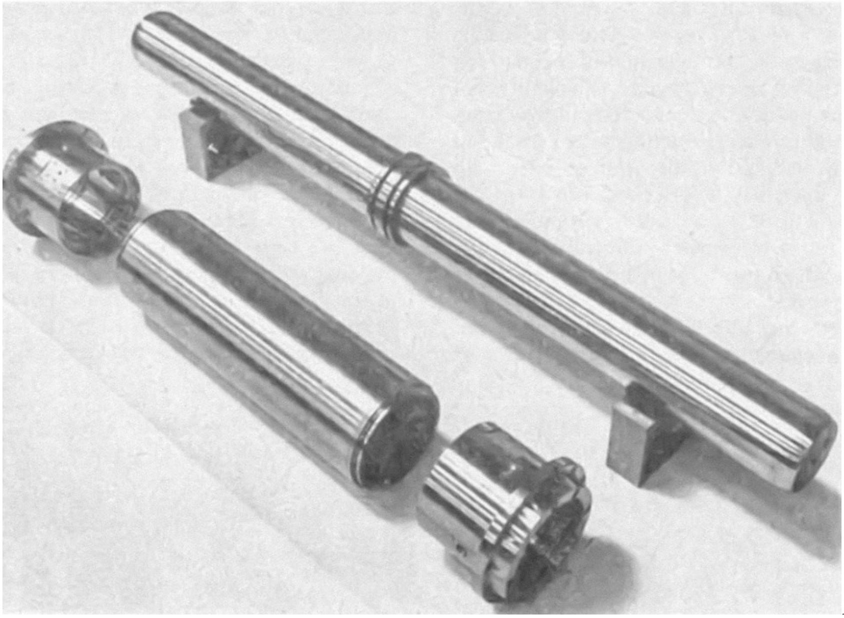


Figure 8.1 Exploded view of combined hydrostatic actuator and slideway system: the end caps include complete hydrostatic bearing systems (by permission of Institution of Mechanical Engineers)

The design of these machine tools included that of a Pelton turbine, as shown in Figure 8.2. The Pelton used oil at 2000 lbf/in^2 (13.8 MPa) to drive a high-powered, high-speed spindle, so that metal-removal would be at its maximum rate.

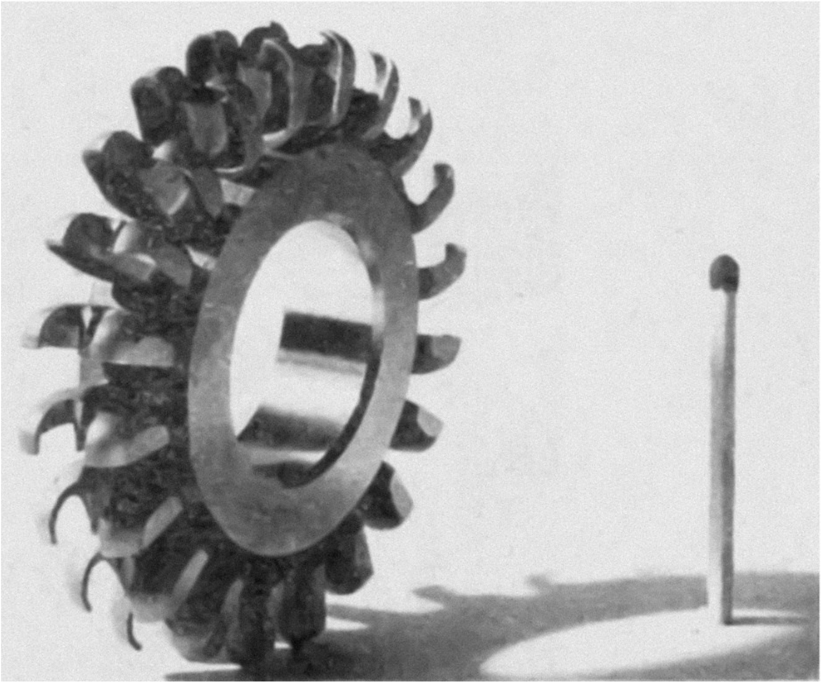


Figure 8.2 Pelton Turbine Wheel providing a 20 bhp (14.9 kW) spindle drive at a speed of 24 000 rev/min (by permission of the Institution of Mechanical Engineers)

These machine tools worked completely automatically, without manual operation. Work was thus loaded and unloaded on pallets; cutters were changed and set to length without needing pre-set tooling, and chips from machining were disposed of and conveyed to a collection point for baling. Hydraulic servomechanisms controlled the machine tools.

Position feedback was measured from linear and circular gratings with Moiré fringe reading heads. This automatic machine tool system required supplementary software to control its operation, and an IBM 1130 computer was installed for the purpose of issuing and scheduling components and materials.

A new building was built for the first SYSTEM 24 at Deptford. Workpiece preparation was carried out at one end of the machining area, and a mezzanine floor was installed above the machine hall for the data and control equipment.

The power supply, hydraulics and swarf disposal aspects were situated in a cellar below the machine area.

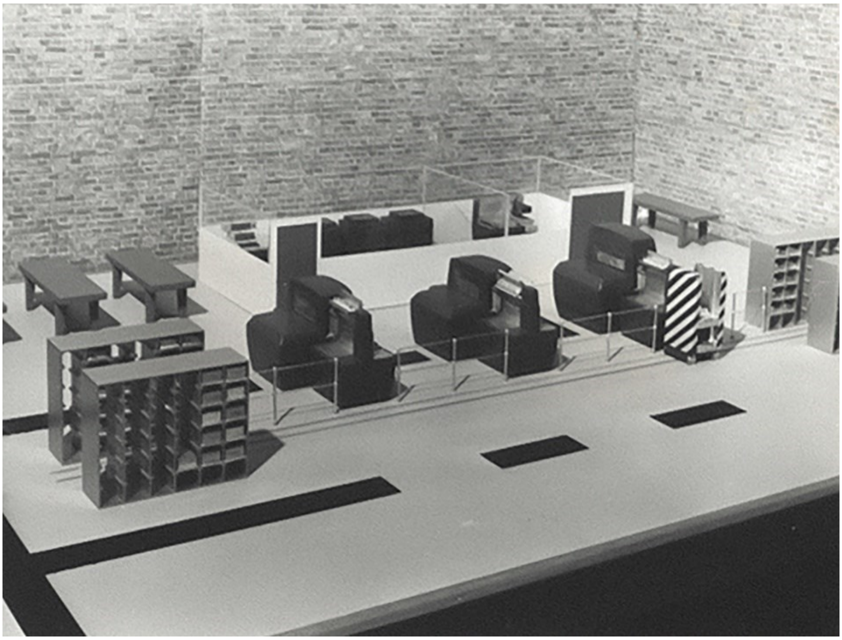


Figure 8.3 Model of machine tools arrangement for SYSTEM 24

Figure 8.3 shows a model of how the machine tools were positioned in a single row, spaced 3275 mm apart. (See also Figure 7.5 shown in Chapter 7) A loading unit stood next to each machine. A "pigeon-hole" style pallet-rack was positioned adjacent to the loading units; a servo-controlled pallet (the "MOLAC" – "Molins on-line automatic conveyor") ran on either side of the pallet rack.

The rack could accommodate 72 pairs of pallets per 3285 mm run. This storage capacity could satisfy 18h of continuous operation at a consumption rate of four pairs of pallets per hour per machine: a 15 min average cycle time.

A row of worksetting stations in sets of three ran along the other side of the rack-conveyor; interposed between them were re-setting inspection machines.

The design of the worksetting machines required careful scrutiny in terms of ergonomics, communication and the need for high efficiency. With these conditions met, semi-skilled operators could be used to attach the workpieces to the pallets.

Facing each operator was a display panel for the worksetting station. The panel presented them with the following information:

(a) a function display, showing “set”, or “reset”, or “unload”.

(b) a two-digit numerical indicator, that included “+” or “-” signs.

(c) a communication system for connection with the control room by loudspeaker – microphone.

The worksetting stations were set in units, three pallet pitches wide – 1095 mm and 1460 mm; the 730 mm wide rear section next to the MOLAC was designated as the pallet delivery, collection and storage rack. It could hold two pairs of pallets on delivery and one on collection. This rack acted as the buffer store between the MOLAC and the worksetting station.

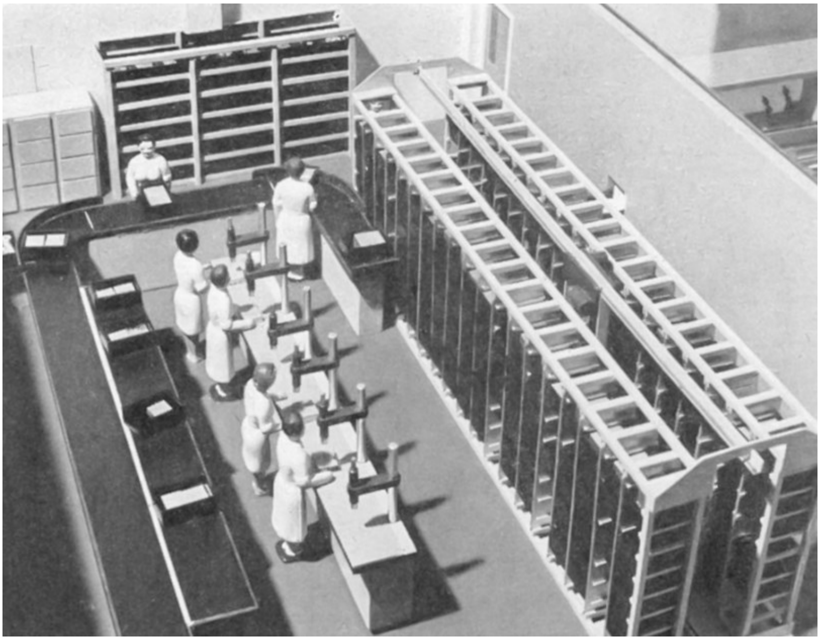


Figure 8.4 Model of Workpiece Preparation Centre (by permission of the Institution of Mechanical Engineers)

Two linear "routing conveyors" delivered material to and from the neighbouring workpiece preparation centre, as indicated in Figure 8.4. Bins full of material were conveyed automatically from the bin rack in the workpiece preparation centre to every worksetting station; the return conveyor allowed bins, finished materials and tooling to be returned.

Each worksetting station possessed electronic data acquisition systems. By these systems, both pallet and bin numbers could be read, and these data sent to the computer.

Parts to be manufactured by the SYSTEM 24 were allocated a part number and the quantity to be made over a period, for example, of ten days. This requirement was then entered into the SYSTEM master file tape.

SYSTEM 24

DAILY MATERIAL SCHEDULE

PART NO.	QUANTITY	BILLET CODE	BILLET LENGTH	BILLET WIDTH	BILLET QUANTITY
424760	24	006	240	225	8
317298	12	002	190	100	4
398712	64	011	270	275	16
471332	16	003	250	150	4
388644	12	018	210	200	2
563233	80	007	185	125	40
410869	28	006	290	225	28
515423	96	012	200	175	20
342453	16	008	280	250	3
465772	22	011	265	275	4
385491	64	012	290	175	16
550762	6	007	250	125	2
419769	20	010	220	250	4
541198	36	004	195	150	12
324878	48	013	260	200	8

Table 8.3 Example of Daily Material Schedule (after Williamson (1968)

Next, these parts were put into groups, and quantities were allocated for manufacture on specific machine tools under a "daily master schedule" and "machine program list" as part of the daily master file transferred to the SYSTEM 24 computer.

The daily material schedule was given to the Molins' Materials Store in advance, usually by a few days (Table 8.3). The materials - usually light alloy billets, rolled sheets or castings - would be prepared to the appropriate sizes for use over some days. A weekly material schedule was prepared by the computer for this purpose. The prepared materials were mounted on trolleys for transfer to a workpiece preparation centre for manufacturing on the given day. The centre received the material schedule and machine program the day before machining.

The system batched the metal blanks, workfixing devices and part numbers in numbered bins. They were placed in the bin rack and dispatched to the worksetting station the next day.

An online IBM 1130 digital computer controlled the entire procedure, with the daily master file extract already in its store.

The system held all data needed for workpiece preparation and fixing: drawing of its blank, drilling template, worksetting diagram and data, a list of worksetting devices needed, and if necessary, information on resetting conditions and devices needed.

A bin rack, to which the MOLAC could run, was situated along one wall of the workpiece preparation centre. The bins to be put on a conveyor were stacked at the correct numbered location on the rack. An empty bin would be selected, and metal blanks would be manually placed in the bin, with the drawing and drilling template, and conveyed to the section for the specified machining operation to be undertaken. At the following stage, the drawing and template would be replaced in the bin by a toolbox holding the workfixing devices and the aperture card.

Finally, the bin would travel and be positioned for checking by an electronic reader. If the correct contents were confirmed by the reader, the aperture card would be placed in the reader. Simultaneously, the card (order part) number would appear. The bin number was entered against the part number in the computer.

The bin, duly completed, was placed on the conveyor; the MOLAC took it for storage in the correct rack position.

This entire procedure was repeated until the rack contained the numbered bins which held the workpieces, tooling and data for use the next day. The computer then instructed them to be automatically transferred to the correct work setters.

8.3 Worksetting

The computer determined the requisite number of pallets required to machine parts. It also allocated a work setter for the machine tools to be used for each operation. The work setter delivered the appropriate bin, whose bin number was read automatically on arrival. The worksetting MOLAC delivered the first pair of pallets allocated for the machining. Their arrival prompted the start of the timing for the worksetting operator, who set in motion the procedure by which the workpiece was presented to the tooling. When this sequence was completed, the pallet was put into the “out” rack, which had two electronic pallet number readers. The countdown ceased when the pallets arrived on the rack. The computer then received instructions that a pallet pair with identical check numbers was to be collected. The bin number and worksetting station numbers were given as checks that the information was correct.

The worksetting MOLAC picked up the pallets and transported them to the storage rack. This procedure was repeated until the required quantity of blanks for the job number had been placed on the pallets.

This sequence enabled an eight-hour day shift to deliver sufficient work to the storage racks so that the machines could be kept running through an unattended 16-hour night shift. The number of work setters needed was in inverse proportion to the cycle time.

The pace of the work setters set the work input rate of the system. So that their pace was kept reasonable, the residual time for each setting operation was noted by the computer. A display showed the worksetting countdown and the cumulative total to the work setter.

The control room also received the cumulative total. With this information, the system controller could monitor progress against the schedule and take remedial action were necessary.

8.4 Machining

The computer next instructed the MOLAC to transfer a pair of pallets to the specified machine tool for machining (after machining, the parts would be taken for cleaning).

The machining programs were recorded on magnetic tape. The machine tools were equipped with magnetic tape readers, run from the control room. On receipt of the correct pallet and magnetic tape cassette location signals, the machine tool became controlled by the information on the magnetic tape. When a signal indicating “end of tape” was sent to the computer, the pallets on the toolbar were ejected, and the pallets were placed in the collection-delivery position of the loading unit. In the event of an error, an alternative “machine fault” signal would be transmitted, and the machining cycle stopped. On correction of the fault, machining would be resumed, with the computer returning to the appropriate part of the program.

By reading the numbers on the next pair of pallets, the computer would know that the cycle had been completed. The MOLAC would collect the pallets and relocate them for the next set of operations on another machine tool, as instructed by the computer. This procedure would be continued until the desired machining had been completed. The pallets would finally be returned to the rack.

Williamson described how the tool parts were chosen through the signals from the magnetic tape program. About 140 to 210 cutters were usually available for the two machine tools typically used in each machining operation. If others were needed, the MOLAC could collect these from a toolbar store at the pallet rack. The computer could also check the accuracy of parts machined, through tape-controlled automatic inspection machines, fitted to the machine tools. If the accuracy was confirmed, the machining could continue. On identification of errors, the machining would be suspended until the fault had been corrected.

Finally, computer control was employed to review the state of the pallet store and decide on the most appropriate conditions for unloading and resetting. Nonetheless, provision for human intervention was also included through the system controller of the workshop. The information received also gave a summary of daily performance.

8.5 Resetting

Special equipment was built to handle machining on the underface of components. A pallet pair would be moved to a workpiece resetting machine, sited between the worksetting machines. The equipment incorporated two microscopes with Zeiss oculars and Ferranti diffraction grating measurement systems with which an accuracy of 0.0025 mm could be ensured. With the pallet fixed precisely on the worktable, the workpieces would be removed from the tooling. Next, either the tooling would be changed or a fresh pallet would be found with the required re-set tooling. The machining on the underface would then be carried out.

8.6 Unloading

On completion of machining, the MOLAC would move the pallets from the storage rack to the worksetting station, to which an empty bin would be sent by the computer. The finished parts and the tooling would be placed in the bin, and the return conveyor would then transport it back to the workpiece preparation centre. The computer would print a note for the bin indicating whether further finishing, such as deburring, was required or confirming that the parts were completed. The parts were then removed and placed in an unnumbered bin, mounted on a trolley for appropriate dispatch.

8.7 Software

The MOLINS SYSTEM 24 used computer software that took account of a machine failure and optimised the machining workload until the fault had been remedied. The benefit of computer control over manual operation was that large quantities of data could be analysed without concern of human error or fatigue. A major criterion was that computer-checked tasks could be entered into SYSTEM 24. Unexpected mechanical or electrical failure was estimated to account for up to five per cent of time lost, giving sufficient time for repairs to be performed.

IBM (International Business Machines Ltd) participated in the development of SYSTEM 24. Molins had already been purchasing IBM equipment and software for use in manufacturing control. It seemed a logical step that IBM collaborate with Molins along the entire journey, from marketing to manufacturing. Eddie Nixon, the head of IBM in the UK, pulled out all the stops, and his staff made many visits. Systems analysts bombarded Williamson and his colleagues with questions and surveys as huge sales were envisaged. A pilot SYSTEM 24, which would use an IBM operating system, was planned for IBM's plant in Rochester, Minnesota.

8.8 Performance

Williamson went on to show the advantage of SYSTEM 24 over conventional manufacturing in terms of time, cost, people and space, as indicated in Figure 8.5.

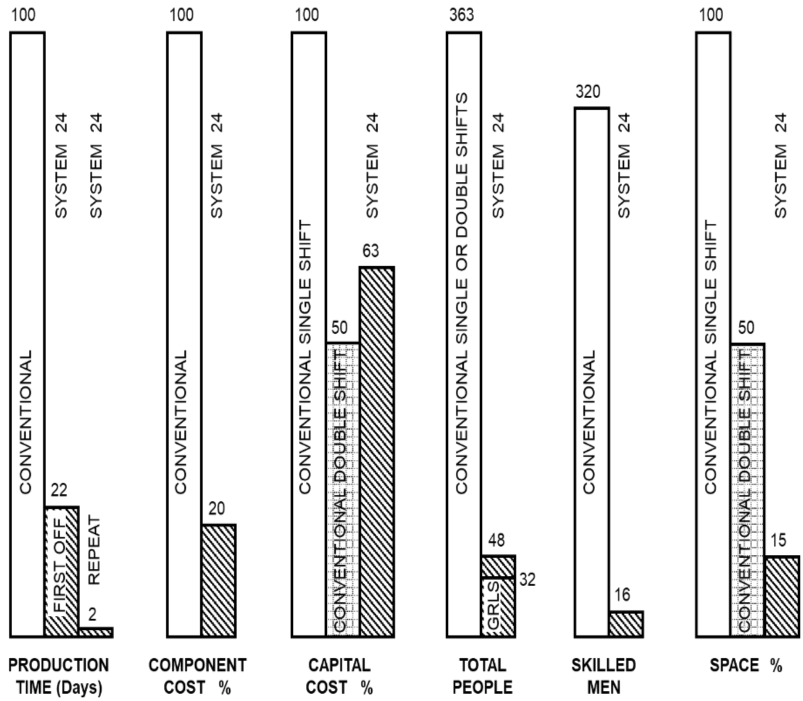


Figure 8.5 Comparison between Conventional and SYSTEM 24 Manufacture (by permission of the Institution of Mechanical Engineers)

Function	Time for 12 components, minutes		
	Conventional	Conventional NC	SYSTEM 24/CAD
Design, drawing and specification . . .	120	120	20
Methods planning . .	30	30	—
Part programming . .	—	480	—
Tape preparation time (including punched tape) .	—	60	5
Worksetting . . .	206	50	10
Machining . . .		96	12
Unloading . . .		20	4
Bending		6	6
Total time for first batch .	356	862	57
Total time for subsequent batches . . .	206	172	32
Total machine time for subsequent batches .	206	96	12

Table 8.4 Comparison between Conventional, Conventional NC and SYSTEM 24/CAD Design and Manufacture for the bracket shown in Figure 8.6 (by permission of the Institution of Mechanical Engineers)

He presented the striking output in one hour from a twin-spindle milling machine (see Chapter 7, Figure 7.4 (a), (b)). Williamson explained how a complementary group of machine tools could offer major benefits in cost and time, using examples of aircraft engine components that had required five-axis milling.

He gave a further example of a simple, light alloy angle fixing bracket, which required holes and slots in various sizes and accuracies and a range of machining and bending operations. (Table 8.4, Figure 8.6)

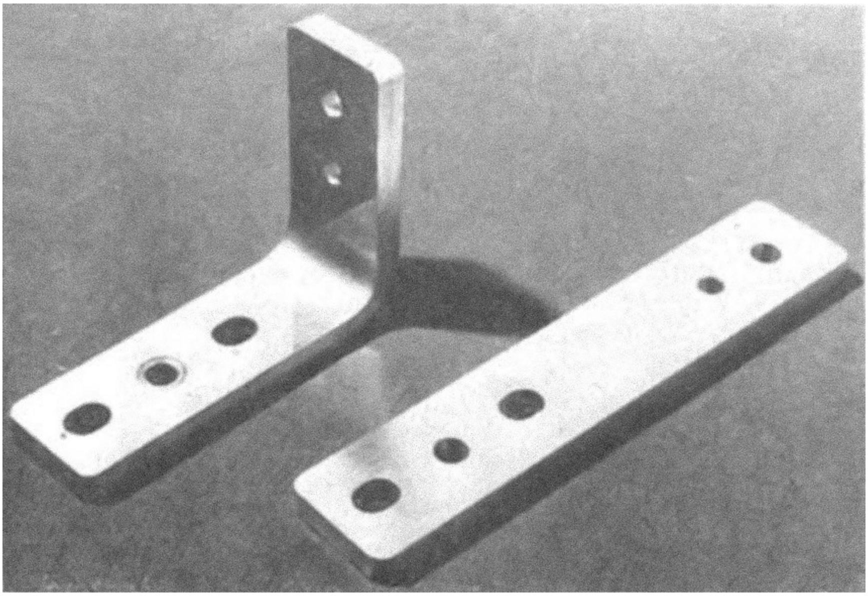


Figure 8.6 Example of Fixing Bracket produced by SYSTEM 24 (by permission of the Institution of Mechanical Engineers)

Conventional mechanical methods took about 206 minutes to make 12 such brackets. He discussed how an entirely computer-aided process was developed, with SYSTEM 24 being used to make the same set of brackets in 12 minutes.

He completed his presentation by drawing attention to the use of advances in computer-aided design, which would create a new interface between design and manufacture, which has arisen in the intervening time since he described his invention in 1968.

Figure 8.7 shows how Molins advertised the revolutionary system of manufacturing.

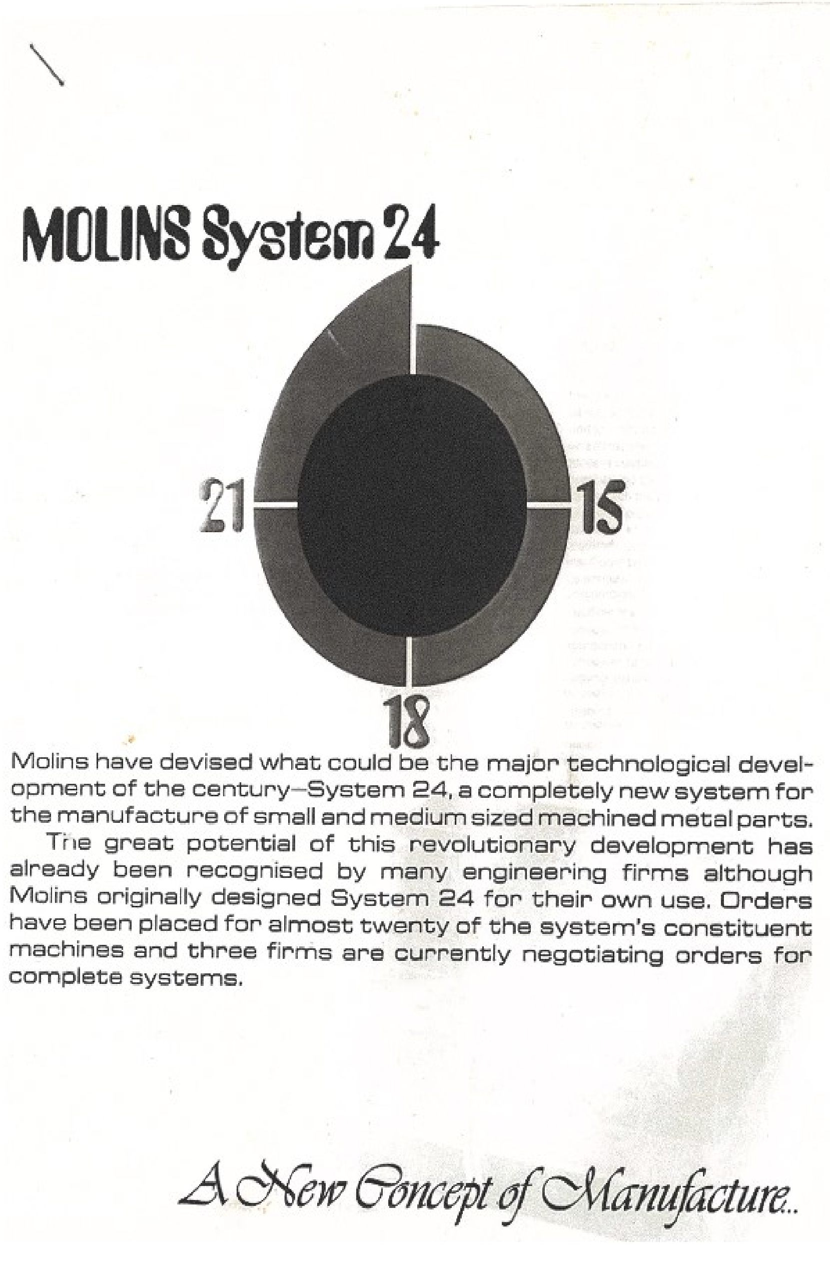


Figure 8.7 An Advertisement for SYSTEM 24 (courtesy of Molins)

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Chapter Nine: Management Changes at Molins

9.1 Management Changes

The extent of the effort to achieve SYSTEM 24, together with IBM's contribution, led the Molins' Board to appoint a new services director. A new layer of middle management was introduced, bringing in extra staff and causing extra expenditure in salaries, and as a result, less effective communication in getting the work done. Morale within Williamson's groups deteriorated.

In 1967, the managing director announced that he was taking early retirement. He had been the mainspring through whom Williamson and the Chairman had the support needed to drive forward SYSTEM 24. The project required Molins to borrow about £2M just before he was due to retire. To raise the money, the main shareholders had to be consulted. The Company was 51 per cent owned by the Chairman and his family and 49 per cent equally by the "Associated Companies", B A T (British American Tobacco), and Imperial Tobacco. For their approval, the latter demanded an extra per cent or so of the shares. They now controlled Molins.

With these changes, a new Managing Director (MD) was found and approved by the Associated Companies. Along with him came an accountant as finance director. The new managing director had been an airline pilot who had been responsible for introducing the Comet jet fleet in BOAC. He had spent much of his life flying aircraft across the Atlantic Ocean. He left BOAC to join Smiths Industries, where, for three years, he helped to introduce the blind landing systems for the BEA (British

European Airways) Trident aircraft. Through this, he had gained some insight into highly advanced engineering.

One of his first actions was to draw on his experience at Smiths and produce an operations manual. This thick document explained how everything was to be done, even going as far as how to obtain a pencil. Hitherto, the staff in Molins had been highly effective and well-motivated, knowing their jobs and how to do them, albeit informally, but working as a team. The MD's right-hand man, his finance director, had little direct experience in dealing with the ethos of a firm like Molins. His main purpose was simply to handle the cash. Soon, they and Williamson were at arm's length. Although the MD had claimed that it was the enthusiasm and technological innovation of SYSTEM 24 that had attracted him to Molins, he and his finance director were now questioning the financial outlay needed to achieve the fruition of the research and development.

The project was further jeopardised when the Molins family decided to float their shares on the Stock Exchange. To cope with the rise in the cost of living in the 1960s, they wanted more cash in hand rather than the equivalent in dividends. A successful launch required a balance sheet that demonstrated a good return on capital; this became a priority over the next four or five years. It meant that expenditure, even if desirable for the long-term well-being of Molins, would reduce the share price at flotations. In that context, the SYSTEM 24 development was regarded as outwith the direct trading of Molins. The research and development and exploitation costs were now queried more than ever.

The finance director regarded the entire project as "blue skies" research and opposed its continuation. He had supporters within the firm, and they helped convince him that the well-established, traditional industrial practices that had helped to grow Molins were enough for it to stay in business. To them, SYSTEM 24 was an expensive pipe dream with little prospect of financial success. It had technical flaws and difficulties that were standing in the way of success.

In 1966, Alexa Williamson suspected that Theo's health was breaking down. Anaemia was diagnosed. Williamson was bleeding internally from an ulcer in the oesophagus caused by a hiatus hernia. In September 1969, he entered Nuffield House in Guy's Hospital, London. Assurances that a perfectly simple operation was all that was necessary became a two-week nightmare during which he fought for his life. He remained in the hospital for several months. During this time, the Molins senior staff took the opportunity to re-arrange the production of SYSTEM 24, and work was effectively stopped. Very few people outside a select circle knew what was going on, and rumours abounded. SYSTEM 24 was reported to be presenting technical difficulties.

The mechanical precision recommended for SYSTEM 24 was claimed to be too extreme and its software was also said to be a problem.

IBM withdrew from the project. First, they were concerned that Molins restructured management would deny them logistical and spare support for the proposed operation in Rochester. Second, their staff manager there was transferred to another IBM plant, and his replacement was less enthusiastic about taking on new, and possibly problematic, unproven technology. Years later, Williamson reflected that for new technology to succeed, you need the backing of the big industrial players, like IBM and Rolls-Royce, and you should not try without it. IBM’s withdrawal was a bitter blow.

At this juncture in 1969, the SYSTEM 24 project was reckoned to be within six to eight months of being completed. The D S M Building had been constructed specifically to take the SYSTEM 24 project and had been fitted with £500,000 of machine tools from the Ministry of Technology. The managing and finance directors insisted that the money should be returned.

On his return to work after his illness, Williamson promptly refuted the criticisms of the mechanical precision needed for SYSTEM 24. He accepted that it was a challenge but was not insurmountable, and he was confident he could deliver the precision of two microns (at a time before this degree of manufacturing precision was common). Without such precision, the machines would have been much less useful.

The criticism of the software was also rejected by Williamson, who maintained the SYSTEM had the right architecture from the start. It could run from an IBM 1130, a machine with much less capability than 21st-century computers, and do all that was necessary. (IBM did order one SYSTEM 24, which was completed in 1972).

Discussion with Alexa led Theo to decide to carry on with the remaining SYSTEM 24 work. Many of his loyal team came to see him, frustrated at the blocking of their efforts to pursue its further development. However, Williamson’s patience finally ran out at a Board meeting in September 1973, and he resigned from Molins.

Ironically, worldwide patents had been filed during the course of the development. Many millions of pounds of royalties continued to be paid to Molins despite the development project being terminated. The fundamental patent in the USA was almost abandoned except for the quick thinking of an attorney there working for Molins. He completed and filed the fundamental patent at his own expense. The outcome was that for every flexible manufacturing system sold in the USA, a royalty was paid to Molins. Indeed, USA Patent Law required that for every FMS in the world that was used to make material exported to the USA, a royalty had to be paid for the life of the patent.

Hewlett-Packard had two FMS running 24 hours a day for almost 20 years until 1990, to the same precision and accuracy envisaged by Williamson. The firm had realised that FMS would revolutionise their manufacturing operation, which it did.

9.2 The Royal Society

Despite Williamson's difficulties at Molins and previously at The University of Edinburgh, his engineering had not gone unnoticed. He was elected as Fellow of The Royal Society (FRS) in 1968. Mrs Williamson was to comment many years later that this distinction gave him much pride and a sense of fulfilment and compensated for the earlier failures, especially in his undergraduate studies.

9.3 D.Sc. Heriot-Watt University

Back in his home town, the universities followed suit. In 1971, Heriot-Watt University conferred the degree of Doctor of Science on him. (Figure 9.1)

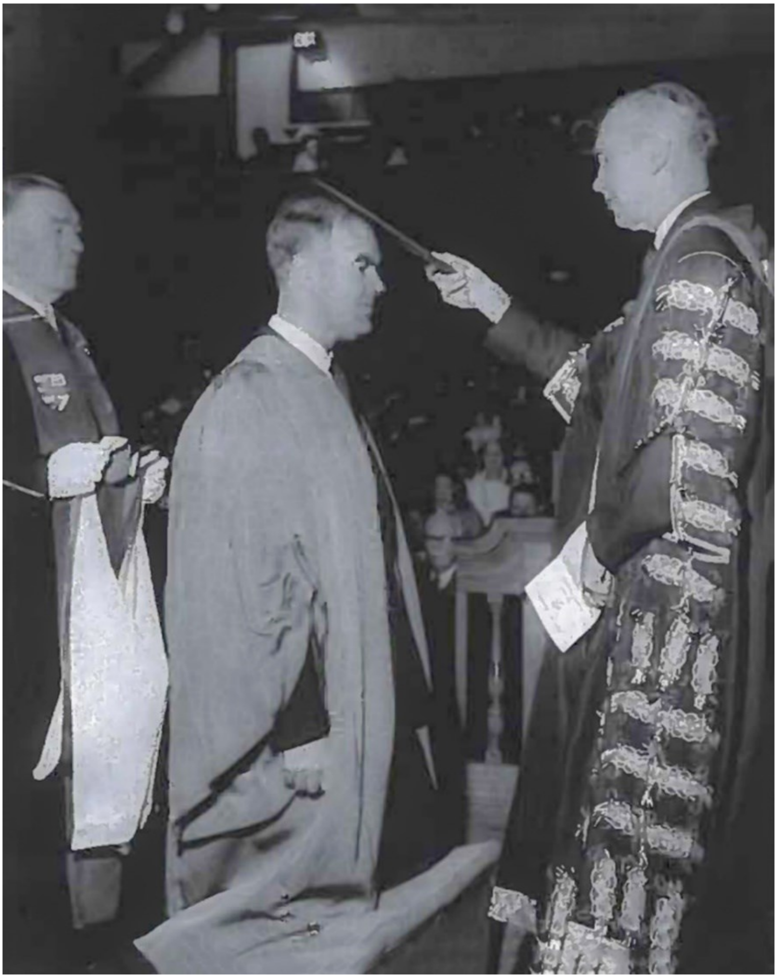
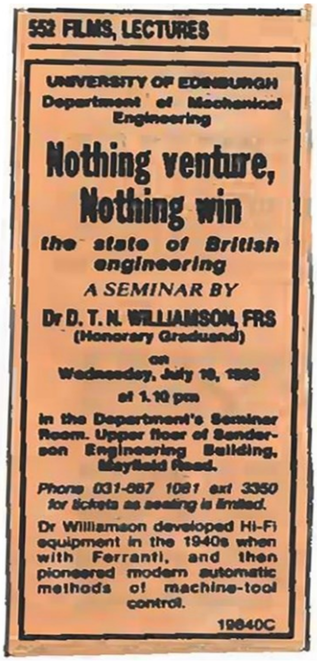


Figure 9.1 D.T.N. Williamson receiving the D.Sc. degree. (by permission from "The Scotsman")

9.4 D.Sc. The University of Edinburgh

His alma mater, The University of Edinburgh, conferred on him the honorary degree of Doctor of Science in 1985. This marked his first return to the Engineering departments. On this occasion, on the day before graduation, he was given a tour of the laboratories to see the fresh work in progress, from the wave power developments to the outcome of his SERC work on electrochemical machining. He was invited to give a talk in the Department of Mechanical Engineering. (Figure 9.2) to which many of his old colleagues from his Ferranti days came to listen.



552 FILMS, LECTURES

UNIVERSITY OF EDINBURGH
Department of Mechanical Engineering

Nothing venture, Nothing win

the state of British engineering

A SEMINAR BY

Dr D. T. N. WILLIAMSON, FRS
(Honorary Graduand)

on
Wednesday, July 16, 1986
at 1.10 pm

in the Department's Seminar Room. Upper floor of Sanderson Engineering Building, Mayfield Road.

Phone 031-667 1081 ext 3350 for tickets as seating is limited.

Dr Williamson developed Hi-Fi equipment in the 1940s when with Ferranti, and then pioneered modern automatic methods of machine-tool control.

19640C

Figure 9.2 Announcement of DTN Williamson Seminar at The University of Edinburgh, Department of Mechanical Engineering, July 1986 (by permission from "The Scotsman")

Chapter Ten: Williamson's Influence on Manufacturing Programmes in UK Universities

10.1 Background

Williamson's outstanding achievements in manufacturing engineering drew the attention of public bodies who urgently needed the services and experience of a practical industrialist.

10.2 Economic Development Committee for Mechanical Engineering (EDC)

In 1969, he was invited to join the Economic Development Committee for Mechanical Engineering, part of the National Economic Development Office (NEDO). Sitting alongside other senior industrialists and trade unionists, Williamson highlighted the stark reality of the parlous state of the British mechanical engineering industry. At that time, it ranked below that of the paper, food, drink, tobacco and chemical industries.

It prompted his NEDO discussion paper entitled *"Trade Balance in the 1970s: The Role of Mechanical Engineering",* published in 1971 (Williamson (1971)).

Williamson included data from the Department of Trade and Industry that demonstrated how the British rate of growth in gross national product (GNP) per head of population had become considerably less than that of other countries over the years 1955 to 1967, notably Germany and Japan.

Whilst the British mechanical engineering industry in 1967 still led other industries in its net output, its share of UK exports had fallen considerably.

The bulk of mechanical machinery exported was based on simple design and manufacture that other countries could readily learn to design and make themselves. Williamson warned that the UK's share of the overseas market would soon vanish. Unless the UK started to design more advanced mechanical machinery, he predicted that the UK trade balance in mechanical engineering would soon decline further, as indicated in Figure 10.1 (from his NEDO paper).

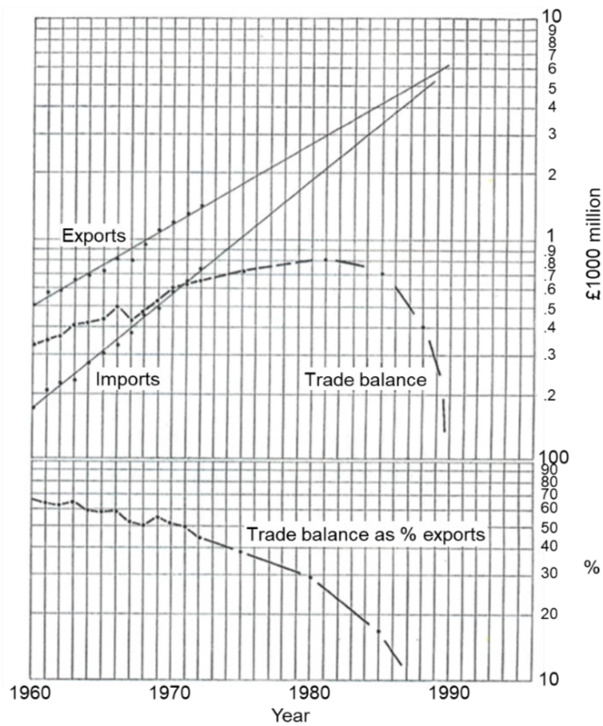


Figure 10.1 Trade Balance for Mechanical Engineering Industry in 1968 (after Williamson (1971))

In 1967, imported machinery was better designed and had superior technical performance than its UK counterparts. Williamson advocated that the UK had to develop machines of more advanced design to meet the overseas challenge. His view aligned with that of the Institution of Mechanical Engineers, which had proposed the establishment of a Design Council in 1968 and the Feilden Committee, which had called on UK industry to foster better design in 1966.

At that time, the UK mainly held advanced technology in aircraft and electronics companies, so whilst British R and D held a high world ranking, its application in other more traditional industries was lacking. The number of entrepreneurs and start-up companies looking to seize opportunities to apply UK R and D lagged greatly behind that of other major industrial nations, notably the USA.

Williamson's appreciation of the UK manufacturing industry's challenges and his vision of how to overcome them saw him join the Engineering Board of the Science Research Council.

10.3 Science Research Council (SRC)

The SRC Council appointed Williamson as chairman of its Manufacturing Technology Committee in 1972. He fostered the establishment of the "Teaching Company Scheme" (TCS), discussed more fully below. Despite initial opposition and misgivings from senior academics, the TCS grew to become one of the most successful examples of UK industry-university cooperation, and its successor, the Knowledge Transfer Partnership (KTP), continues to this day.

10.4 Teaching Company Scheme (TCS)

A working party was appointed by the SRC and Department of Industry to address the scarcity of qualified personnel in manufacturing technology. A new scheme was proposed to improve post-graduate training in manufacturing engineering. It was proposed that well-organised manufacturing firms in partnership with higher education establishments should become "teaching companies". Young graduate engineers under the direction of industrial and academic staff would be appropriately trained so they could advance manufacturing engineering. The practical training would proceed in parallel with academic learning at the University. The SRC, Department of Industry and the University would share the costs.

Williamson first proposed a similar scheme in 1973, based on the successful approach of teaching hospitals. He suggested a new manufacturing company should be formed as a teaching and research firm, for this purpose.

The SRC and Department of Industry published a consultation document on "The Teaching Company" in December 1975. Its aims were primarily twofold: first, to bring more high-quality, able engineers into manufacturing industries, and second, to give them a postgraduate education with industrial experience, thereby providing them with the knowledge to use the resources available in the firm and an understanding of how manufacturing and other aspects of industry were organised and managed. With this training, they would be better equipped to lead others and apply sound judgement. They would also be in a position to facilitate cooperation between industry and academia in order to gain an understanding of the requirements to enable "profitable" manufacturing and to spread this knowledge throughout the UK mechanical engineering sector.

The working party emphasised that the training had to be undertaken in a "live" industrial environment where the management was supportive of innovative manufacturing. The industrial projects undertaken by the young graduate engineers would have to be complemented by relevant courses at the University.

Williamson had stated that the TCS was "the engineering equivalent of a teaching hospital where practitioners, researchers and students intermingle and cross-fertilise ideas, whilst doing a job in a real environment which interfaces with society and where they can bring about changes which intrinsically fit a real situation".

Academics could share their experience and ideas with industry. Industry's challenges and requirements would be presented in the firm where recent graduates appointed by the University as Teaching Company Associates (TCA) would be based. Supervision would be jointly provided by a company employee academic who would be expected to pay regular visits to the company.

The intention of the TCS was to create a strong partnership between industry and higher education establishments. The UK's industrial performance, its profitability, and its management could only benefit.

The TCS was reviewed between 1984 and 1985, about ten years after its conception. Its objectives, as described by S Humble (1989), remained largely the same:

(a) to raise industrial performance through the use of academic resources;

(b) to implement new technologies and ideas to enhance industrial methods;

(c) to promote graduate employment in industry.

Academia itself, its teaching and research, could only benefit from this direct collaboration with industry.

In 1990, the Department of Trade and Industry (DTI) and the Science and Engineering Research Council (SERC, formerly SRC), its main sponsors, undertook further review. At that time, each was contributing about £5M to the TCS, with an additional £200,000 coming from the Economic and Social Research Council (ESRC), and £500,000 per year from the Department of Economic Development in Northern Ireland to enhance the number of TCS in the Province. About 375 programmes were running, mostly with manufacturing companies. About 40 per cent of the direct costs were contributed by the industrial partner, spanning salary top-up for the Associate, equipment, line manager's time (10 per cent), and overheads that took into account space requirements.

In this review, attention was drawn to concerns over the sharing of intellectual property rights (IPR) between the higher education establishment and industrial company, and about the publication of research papers and their possible infringement of commercial confidentiality. At that time, about 60 per cent of the TCS programmes were undertaken in SMEs (Small and Medium Enterprise). The question was addressed as to whether the work of the Associate was appropriate for registering for a higher degree. A high proportion of women had become TCAs. The scheme was regarded as appropriate training for the TCA aiming towards Chartered Engineer (CEng) or through professional engineering institutions. There was concern about overheads for the HEAs as payments for replacement teaching or research work were now being raised.

Whilst some of Williamson's influence could be seen in some of the TCS programmes then running – audio equipment, cutting tools, surface finishing, CAD/CAM, automated production techniques, and flexible manufacturing systems are examples - other areas and projects were also being supported. They included the manufacturing of artificial limbs, ventilation systems for livestock production, fertilisers, financial transaction systems and parallel processing techniques for very large-scale integrated circuits (VLSI).

The concept of the TCS as an industry/academic form of the Teaching Hospital was no longer considered valid. A change in direction towards technology transfer and graduate training should now be its purpose. The TCS was replaced by the Knowledge Transfer Partnership (KTP) in 2003. It was now led by "Innovate UK", the public body under the auspices of the Department for Business, Energy and Industrial Strategy (BEIS), and was supported by 17 public bodies. Its main strands still apply:

(a) a company (extended from industrial firms, now to public and voluntary bodies)

(b) a higher or further education institution, and a recent graduate.

The objective is still to improve competitiveness and productivity by identifying needs and finding innovative solutions. At that time, about 1000 KTPs were running.

The Engineering and Physical Sciences Research Council (EPSRC, formerly SERC) remains one of the sponsors of the KTP. In its Annual Report for 2017-2018, it reported to the UK Parliament that it contributes £2m annually with 120 projects through 49 academic bodies. SMEs are now involved in 65 per cent of all KTPs. EPSRC is one of seven research councils partnering with Innovate UK in running KTPs as part of the latter's Knowledge Transfer Partnership Network.

In 2018/2019, Innovate UK reported that it had provided £30m for KTPs, thereby creating new jobs for graduates. The Knowledge Transfer Partnership continues to support innovation in the UK business community, and in 2018, UK Research and Innovation (UKRI) was established. KTPs now form 5.5 per cent of UKRI programmes. As of 2018/2019, there were 550 KTPs in post. For every £1 invested, the KTP was estimated to be generating £8; it made the KTP one of the biggest graduate recruitment mechanisms in the UK, with 810 UK organisations and 100 universities or research organisations supporting 851 associates.

From the unsure start of the TCS in 1975, its successors are now significant drivers of the UK industrial innovation strategy.

10.5 SRC (SERC) Grinding Programme

A "Grinding Technology" programme, promoted by Williamson as Chairman of the SERC Manufacturing Technology Committee, was initiated in 1974. He had been convinced that, in especially the automotive and aerospace industries, there were considerable advantages if grinding could be properly developed for metal removal rather than mainly for fine finishing. In the latter practice, it was heavily dependent on the manual skills of grinding machine operators for the attainment of key results such as reliable output quality and efficiency. They themselves were a rapidly diminishing group, and as such, fuller use of grinding would require an entirely fresh strategy.

Williamson was able to draw on his own personal experience and achievements in computer numerically controlled (CNC) machining and advances in adaptive control and in-process gauging (i.e. automatically controlling the rate by which stock is removed from a part until the required size is obtained).

Ambitious targets were set: high rates of metal-removal to required geometry and surface finish; increase in metal removal rates as a finishing process; and the development of adaptive control for its inclusion in automatic control systems.

Fourteen universities and polytechnics joined the programme, either for individual projects or in groups, leading to recognised centres for grinding expertise.

A close liaison with industry was a constant, integral part of the programme. Major UK companies would utilise their findings, for example, for creep-feed grinding (that is, abrasive cutting in which all or most of the stock is removed in a single slow pass over the component) that is applied in the production of jet engine turbine blades. New grinding fluid coolants were developed that extended their life usage, thereby delivering cost savings and improving long-term performance.

The need for so much prior dependence on manual skills for efficient grinding was tackled through the incorporation of adaptive control on a novel grinding machine that allowed both stock removal and finishing cycles. There was an initiative to investigate high-strength abrasive grinding wheels. SERC commissioned a design study for a production cylindrical grinding machine based on these developments that could serve the purposes of, especially, industries involved in the production of large batch sizes.

The grinding partnerships also recognised that innovative measurement methods were a key instrument rather than those dependent on human skills. To that end, electro-optical inspection systems were investigated that facilitated the measurement of surface shapes and finish of two- and three-dimensional contours. Methods were developed for accurate measurement and analysis of holes and shapes based on either dimensions or area. These procedures, based on the measurement of length, area, chord and perimeter, enabled a major step forward in grinding practice.

Those industries involved in the programme included automotive, agricultural, heavy goods vehicles, domestic appliances and textile and food packaging. The projects were often backed by related studies of engineering design, especially vibration and chatter, of rigidity, and of novel hydrostatic bearings and even investigation of magnetic levitation. Throughout the grinding programme, economic models were developed to facilitate decisions for production management. All this constituted fresh thinking and approaches in research strategy.

10.6 SRC (SERC) Die and Mould Research Programme

At SRC, Williamson was presented with major problems associated with the UK die and mould industry. There was a four per cent per year loss of skilled manual workers, especially those associated with the surface finishing of moulds. The latter practice was reckoned to account for more than one-half the time needed for manufacturing moulds. The problem was particularly acute in moulds for plastics and pressure-diecasting goods, where high manual skills were demanded. Large toolmaking firms were still able to train apprentices to learn these skills from their more senior experienced generation or to use CAD/CAM (computer-aided design and manufacture), which might achieve the same ends. Smaller firms, which made up the bulk of the tool-making industry, were often less well-equipped in either way and were also beset by low-profit margins.

A coordinated programme of research that drew on new manufacturing process technology was put in place. It would put much-needed science into die and mould manufacture, identify university centres of expertise and build their connections with industry.

Ten UK universities and polytechnics took part in a programme that ran from 1975 to 1982 and continued thereafter.

Unconventional methods of machining were at the forefront of the research effort, in particular electrodischarge (EDM) and electrochemical (ECM) machining, as well as related electrochemically-based surface coating techniques.

With EDM, much effort went into the design and the control system that enabled automatic adjustment of machine operations, which might reduce the amount of hand finishing of dies and moulds. The onset of EDM machine malfunctions caused by arcing, rather than sparks, was tackled and led, especially to a novel form of radio-frequency spark detection, which yielded smooth surface finishing. The manual removal of the cusps from the conventional milling of dies and moulds was overcome by the application of a novel combined form of EDM and ECM, termed ECDM or ECAM, which enabled rapid removal without loss of stock metal (ECAM or ECDM relies on erosion by sparks created by electrical discharge in the aqueous electrolyte between the cathode-tool and anodic-workpiece). Machines that permitted EDM of mould cavities, followed by ECM for final finishing, were developed.

New surface coating techniques were investigated. From brush-plating researches, cobalt-molybdenum electro-deposited surfaces were applied over the press tools to improve performance. Ion plating was used to achieve ceramic coatings at substrate temperatures below those that would soften die steels. Titanium nitride coatings were ion plated with hardness over 2500 HV, without softening die steels. Electrochemical brush-plating with cobalt-molybdenum and cobalt-tungsten alloys was investigated for a wide range of dies used in the manufacture of automotive and aircraft engine components.

This family of electrolytic deposition techniques was extended into "electroforming" (that is, thick electroplating in which the deposit is removed from its cathode to yield a free-standing structure). The attraction here was the structure would be the electroformed mould, one face of which reproduced the shape, surface finish and surface texture required of the mould. Iron and the alloys were the main electroformed moulds. Applications were tried on items ranging from industrial automotive components to those for rubber "O" rings. Superplasticity, which offers high tensile ductility, creep-resistance and wear resistance, notably for polymer moulding, was studied. Commercial applications lay in fancy goods and fashion products.

Science-based research examined heat transfer in dies and applied CAD to make dies for EDM electrodes on NC (numerical-control) machines. With relevance to forging dies, heat treatments of dies and moulds were researched. Attention was extended to plasma nitriding for tool steels and vacuum 'carburising' and 'boronising.' Applications were found where a plasma process offered a better surface finish and heat treatment at low temperatures. Vacuum carburising was innovative in its relevance to tool steels, where wear resistance and toughness were required in the fabrication of high-carbon steel. Boronising offered to increase tool life.

Universities with known expertise in these areas were identified. An industrial co-ordinator was appointed. His job was to pay regular visits to each of the laboratories where the work was progressing and report back to the SERC panel that was composed mainly of industrialists. The Principal Investigators were encouraged to seek out both major companies and SMEs with technological problems and discuss their findings.

The National Research Development Corporation (NRDC), later the British Technology Group, took a vested interest in the programme. Many patents, giving worldwide cover in some cases, were filed. The principal researchers were also expected to have, usually, an SME through whom any equipment could be manufactured or applications developed. Where none existed, they were also encouraged to seek support for start-up companies which could fill this role. This was a formidable challenge, especially for academics. Without the necessary business, financial and commercial acumen, they were being stretched beyond the normal boundaries of academic research. Yet many did so.

Williamson's vision of using academic expertise to turn the tide in the fortunes of manufacturing in the UK was being met.

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Chapter Eleven: Williamson, Man and Family

11.1 Family

Theo Williamson met his wife-to-be Alexa when she took a job as a secretary with Ferranti in November 1949, initially working in the same laboratory as him (Figure 11.1).

Figure 11.1 Alexa Williamson

Her father had a shop-fitting business in Edinburgh. Due to the Great Depression of the 1920s, he was a firm believer in education as a means of improving one's station in life. Her sister became a teacher, and her brother a medical specialist. Alexa was a "Seavac", staying with her father's brother and family in Johannesburg through the years of the Second World War. After school, she spent a year at business college, then went on to Edinburgh University, from which she graduated with an MA. On 8 June 1951, Alexa and Theo were married (Figure 11.2).

Figure 11.2 Alexa and Theo marry in Edinburgh

Shortly afterwards, Alexa met Professor Say, who told her she had married a genius (somewhat daunting for a new wife!). She knew that Theo's failure to graduate BSc rankled with him. He did not talk about it, but it was unbelievable to all who knew him. She once suggested to Theo that he should resit the mathematics examination, but he replied, “I don’t have time”. They were still in Edinburgh when their first three children were born: Ann, Carol and Peter. Alasdair was born in Kent; his father had joined Molins by that time. Alexa knew that Ferranti certainly did not want Theo to leave, but, as Sir John Toothill pointed out, Ferranti had a salary scale that could not be broken, so there was no way Ferranti could match the Molins’ offer. The managing director of Molins at the time was Ted Broome. He became a great friend of the Williamsons. Ted later told Alexa that before he left London on one of his trips to persuade Theo to join them, the Chairman Des Molins said, “I don’t care what you do, but get that man”. The family atmosphere created by Ted Broome at Molins was a major factor that had impressed Theo and encouraged him in the decision to join them. It had been a very difficult decision, as Williamson had found Ferranti in the 1950s and early 1960s a wonderful company to work for. It also had all the hallmarks of a family concern. Toothill had run it by setting up many specialised units led by a head, whom he supported and encouraged up to the limit. Toothill was not a frequent visitor to his departments. He operated by appointing good people to manage for him and then left it to them to get on with it. However, he was not above popping in now and again to see how things were going, especially if he had been asked for some sums of money for some interesting work. One day, he called Craigroyston House and asked to meet the staff on the front lawn. It is said that he was more and more amazed as more and more people continued to troop out of the building. Ultimately, the tally was about 100, perhaps just as many as would fill the building.

Later that decade, Williamson heard that this spirit became dampened somewhat by over-officious administration, which ultimately drove out Sebastian Ferranti, who really built up the company.

There was never any question of Alexa having a career. Theo firmly believed his wife should be just that. With their four children and many guests and visitors, it was a busy and happy life. Their home in Kent was secluded and ideal for family life. Alexa was an enthusiastic swimmer, and although Theo was not – athletic pastimes were not one of his interests, due in part to a history of recurrent ill-health in his childhood - he built a pool in their garden. Any creative and scholastic interests of their children had his full support - Ann went to the Royal Ballet School and later ran a ballet school in Italy. Peter went to Winchester College, and later, when the family moved to Leighton Buzzard, Alasdair became a day boy at Berkhamsted.

11.2 Rank Xerox

About 1973, Theo was offered three Chairs of Engineering. He refused them all, mainly on the grounds that he did not want to become involved in academic life to the age of sixty-five; he had already decided, in any case, to retire early. Rank Xerox was historically part of RX Manufacturing. Its task was conversion – engineering of US office machine designs in accordance with the requirements of individual RX markets, and consequently, to support local manufacturing activities. RX's responsibilities covered all territories outside the USA. Engineering effort was distributed among RX manufacturing sites, including Welwyn Garden City in the UK, and other smaller ones in Germany, France and Spain. In the late 1960s, a decision was made to introduce single-point design for multinational manufacturing. A major European Central Engineering site was created at Milton Keynes for that purpose, in temporary accommodation. It brought together research, machine design and development and manufacturing engineering, as well as essential field engineering efforts. A search began for a suitable candidate for the post of "Director of the Central Engineering Site". The search ended in December 1973 when the RX Group technical director met Theo Williamson for the first time. With his background and reputation in electronics, his renown as the designer of the much-acclaimed "SYSTEM 24" series and his international stature, Williamson met exactly the requirements for the post. He began in March 1974, taking over the temporary accommodation, and started building a team and streamlining the existing organisation. On 1st January 1975, Williamson became Group Technical Director, taking over from his American colleague on the latter's transfer back to the USA. He had an engineering strength of 1,200 and a budget of $25 million.

Reporting to him were the heads of Financial Control, Personnel and Administration, Site Engineering, Planning and Procedures. He maintained liaison with the Director of Research and with the Chief Engineers in the major UK and European Manufacturing sites.

Nine major product development programmes were in progress, covering office machines, consumables and information technology. Examples included work on copiers/duplicators; networking, using broadband interoffice communication networks; the development of computing capabilities, including in-parallel computing; storage and retrieval of information, facsimile product requirements; transceiver technology development; digital modem specifications; consumables engineering that included new toners and properties of paper; and man-machine interface studies. (Note that Alexander Bain, from Inverness, invented an early form of a fax machine in 1842).

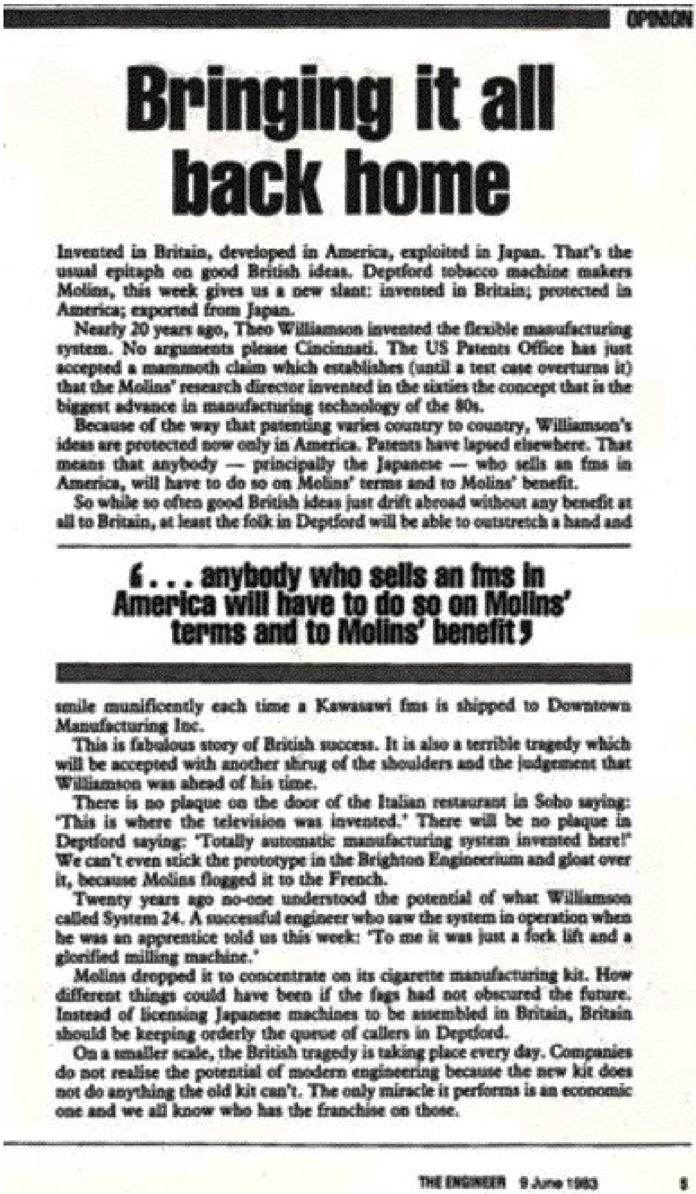
His appointment required him to maintain mandatory contact with universities and other appropriate institutions, acting as the Rank Xerox scout, and keeping an eye on promising technological developments in Europe.

Theo Williamson's understanding with Rank Xerox was that he would work for them for two years, and he left about 1977.

The Williamson family had moved to Leighton Buzzard in Bedfordshire, so Theo's job as European Director of Research was convenient for both Alexa and their children as well as for their father. In the cellar of their new house, Theo installed a workshop. Alasdair often helped his father there, maintaining he learned more from Theo than he ever did at school. This close collaboration continued for the rest of Theo's life.

11.3 Fiat

After his time with Rank Xerox, and whilst in Bedfordshire, Theo was approached by Fiat, Turin, to act for them as a consultant. Flexible Manufacturing Systems was a major attraction for the car industry. They asked him to go to Japan and report on robot control of machine tools. (It proved to be a bitter moment for both him and Alexa at an exhibition in Chicago in 1982, when they saw what the Japanese were demonstrating, and what the UK could have done almost twenty years before, as the Molins research and development had headed in the same direction). The bitterness was ameliorated by their tacit agreement that it was all "water under the bridge". An article published in "The Engineer" on 9 June 1983 reflected on Williamson's vision on what should have been a fabulous story of British success (Figure 11.3).


OPINION

Bringing it all back home

Invented in Britain, developed in America, exploited in Japan. That's the usual epitaph on good British ideas. Deptford tobacco machine makers Molins, this week gives us a new slant: invented in Britain; protected in America; exported from Japan.

Nearly 20 years ago, Theo Williamson invented the flexible manufacturing system. No arguments please Cincinnati. The US Patents Office has just accepted a mammoth claim which establishes (until a test case overturns it) that the Molins' research director invented in the sixties the concept that is the biggest advance in manufacturing technology of the 80s.

Because of the way that patenting varies country to country, Williamson's ideas are protected now only in America. Patents have lapsed elsewhere. That means that anybody — principally the Japanese — who sells an fms in America, will have to do so on Molins' terms and to Molins' benefit.

So while so often good British ideas just drift abroad without any benefit at all to Britain, at least the folk in Deptford will be able to outstretch a hand and

'. . . anybody who sells an fms in America will have to do so on Molins' terms and to Molins' benefit'

smile munificently each time a Kawasawi fms is shipped to Downtown Manufacturing Inc.

This is fabulous story of British success. It is also a terrible tragedy which will be accepted with another shrug of the shoulders and the judgement that Williamson was ahead of his time.

There is no plaque on the door of the Italian restaurant in Soho saying: 'This is where the television was invented.' There will be no plaque in Deptford saying: 'Totally automatic manufacturing system invented here!' We can't even stick the prototype in the Brighton Engineerium and gloat over it, because Molins flogged it to the French.

Twenty years ago no-one understood the potential of what Williamson called System 24. A successful engineer who saw the system in operation when he was an apprentice told us this week: 'To me it was just a fork lift and a glorified milling machine.'

Molins dropped it to concentrate on its cigarette manufacturing kit. How different things could have been if the fags had not obscured the future. Instead of licensing Japanese machines to be assembled in Britain, Britain should be keeping orderly the queue of callers in Deptford.

On a smaller scale, the British tragedy is taking place every day. Companies do not realise the potential of modern engineering because the new kit does not do anything the old kit can't. The only miracle it performs is an economic one and we all know who has the franchise on those.

THE ENGINEER 9 June 1983 5

Figure 11.3 Article in "The Engineer", 9 June 1983 (by permission requested from "The Engineer")

11.4 Life in Italy

In September 1979, Alexa and Theo retired to La Cima at Tuoro sul Trasimeno in Italy. They set out to extend the house they had bought and to construct a swimming pool. Figure 11.4.

Figure 11.4 Alexa and Theo's house in Tuscany

"Do-it-yourself" was a major feature of the building work, with Alasdair and his father continuing their collaboration. Alexa also contributed by painting the house or working in the garden. A new workshop was built at La Cima, where Theo continued to "work for my son", completing projects for Alasdair's company back in the UK. One dealt with the electroforming (thick electrodeposition) of iron on hollow plastic spheres for the electromagnetic properties that could be achieved. Electroforming was a process that had received support from the Science and Engineering Research Council (SERC, now EPSRC) under its die and mould manufacturing programme that Williamson had established during his time on the Engineering Board of the Research Council.

Despite these interests and pursuits, nonetheless, the house extension took much longer than they expected, and often there were problems with precision or the lack of it, much to Williamson's frustration and annoyance. He once proclaimed to Alexa, "I have designed a house that will not fit together". Although Alexa and Theo had been attracted to the quietness of the area (much has now changed since those days), they found it backward in many ways. Things that Theo wanted to do were just unknown there. However, he did manage to design and build a ceiling in their main living area that would provide the best acoustic effects for sound reproduction.

In Italy, Theo Williamson continued his connection with Fiat, also working in his workshop on projects for Alasdair. He also became involved through Professor Nicolas Kurti of Oxford University for several years in the ICUS (International Conference on the Unity of the Sciences).

With GBR Feilden, he organised a Royal Society "Discussion on Manufacturing Technology in the 1980s" publications from which appeared in Philosophical Transactions of The Royal Society, Series A, No. 1250.

In 1984, he started having heart conditions, and he underwent a heart bypass. He then suffered two agonising years of shingles before succumbing to cancer. He died on 10 May 1992.

11.5 Coda

Many of the tributes and obituaries that followed his death in 1992 drew attention to his warning to the National Economic Development Organisation that Britain's trade balance would continue to worsen if the industry failed to give long-term support to the development of high-value-added engineering products. He emphasised the need for more effort in organising innovation and product design excellence and less on what he called "bean counting". He was convinced that the UK could make far better use of its engineering skills, provided it went about it the right way and used its universities more appropriately. Some of the lessons have been learned from this visionary, whilst others remain to be adopted.

In Edinburgh, the local Institution of Mechanical Engineers arranged for a plaque marking his achievements to be presented by its President and mounted at his former home. (Figure 11.5)

Figure 11.5 President of the Institution of Mechanical Engineers, Brian Kent, presents a plaque to the owner of Williamson's former home

The original members of his Ferranti team were able to gather there together with his son Alasdair and members of the Institution of Mechanical Engineers (Figure 11.6).

Figure 11.6 Members of the Institution of Mechanical Engineers, Williamson's former workmates, and guests (left to right: Joe McGeough, John Irvine, Peter Walker, Alasdair Williamson, Alan Bradley, George Goudie, Donald Walker, Robert Nicholson, Owen Stainsby)

Primary seven pupils at his old school, George Heriot's, took part in a competition to create their impression of Williamson's inventions. In Figure 11.7, the amplifier is envisaged as the soundbox, flexible manufacturing is seen as the motor car and the chute as delivering a product from software.

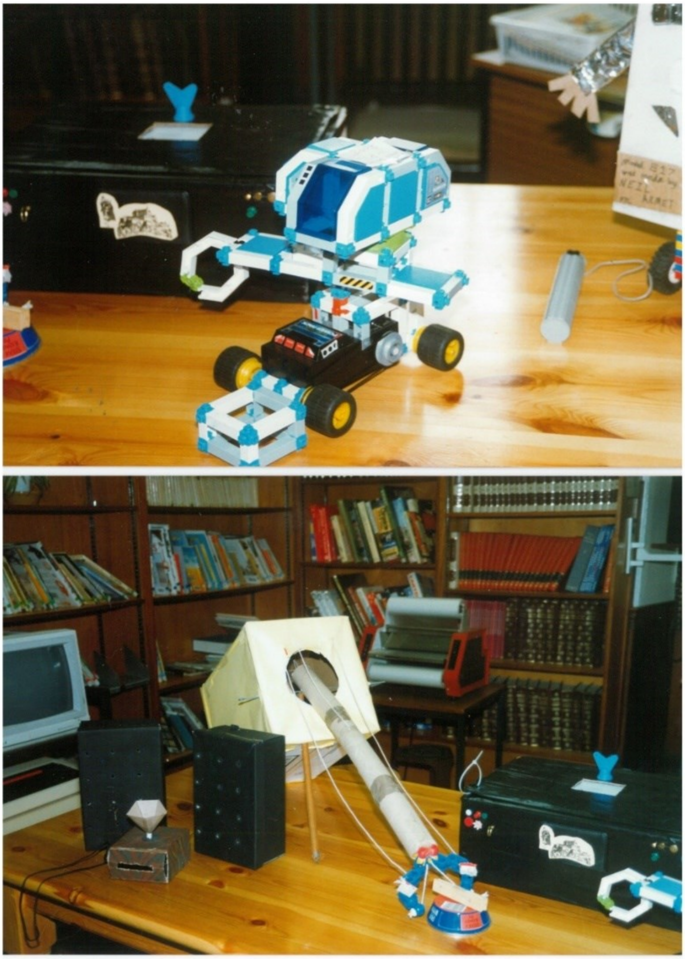


Figure 11.7 Primary 7 pupils at George Heriot's School built models of his amplifier and flexible manufacturing system

Previously, Williamson likened the SYSTEM 24 to an orchestra. He was the conductor. The instrumental players were the 100 or so team who created the music, which became SYSTEM 24. There were no principal soloists. All gave their best. Their achievements marked a milestone in the history of UK Engineering.

Glossary

Adaptive control	The capability of the system to modify its own operation to achieve the best possible mode of operation.
Adiabatic machining	Also known as high-velocity impact cutoff, adiabatic cutting uses kinetic energy (provided by a mechanical, pneumatic or hydraulic press and precise dies) to create a shockwave that softens a narrow, vertical plane through a piece of barstock. The energy is converted into heat faster than the material being cut can dissipate it, and this controlled plastic deformation separates the material.
AF transformer	Audio Frequency (AF) transformers work at frequencies between about 20Hz to 20kHz and are used in audio amplifier circuits.
Airspeed indicator	Instrument that measures the speed of an aircraft relative to the surrounding air, using the differential between the pressure of still air (static pressure) and that of moving air compressed by the craft's forward motion; as speed increases, the difference between these pressures indicates the airspeed.
Amplifier	An amplifier is an electronic device that increases the voltage, current, or power of a signal. Amplifiers are used in wireless communications and broadcasting, and in audio equipment.

Audio amplifier	An audio power amplifier (or power amp) is an electronic amplifier that amplifies low-power electronic audio signals, such as the signal from a radio receiver or an electric guitar pickup, to a level that is high enough for driving loudspeakers or headphones.
Automatic tool changer	An automatic tool changer (ATC) is used in computer numerical control (CNC) machine tools to improve the production and tool-carrying capacity of the machine. ATCs change tools rapidly, reducing non-productive time. They are generally used to improve the capacity of the machines to work with a number of tools.
Backlash	In mechanical engineering, backlash, sometimes called lash, play, is a clearance or lost motion in a mechanism caused by gaps between the parts. It can be defined as "the maximum distance or angle through which any part of a mechanical system may be moved in one direction without applying appreciable force or motion to the next part in mechanical sequence."
Batch production	Batch production is a method whereby a group of identical products are produced simultaneously (rather than one at a time).
Beta radiation	A beta particle, also called beta ray or beta radiation, is a high-energy, high-speed electron or positron emitted by the radioactive decay of an atomic nucleus during the process of beta decay. There are two forms of beta decay, β^- decay and β^+ decay, which produce electrons and positrons, respectively.

Binary system	In mathematics and computing systems, a binary digit, or bit, is the smallest unit of data. Each bit has a single value of either 1 or 0, which means it cannot take on any other value.
Bluespot	The Bluespot Digital Multi-Meter measures AC/DC voltage and DC current and tests resistance, diodes and transistors.
Boronizing	Boriding (boronizing) is a thermochemical diffusion process in which hard and wear-resistant boride layers are generated by diffusing boron onto the surface of material. The treatment of the materials is carried out in a temperature range of 750 to 950°C.
CAD/CAM	CAD (Computer-Aided Design) and CAM (Computer-Aided Manufacturing) CAD/CAM software is used to design and manufacture prototypes and finished products.
Caesium-137	Caesium-137, or radiocaesium, is a radioactive isotope of caesium that is formed as one of the more common fission products by the nuclear fission of uranium-235 and other fissionable isotopes in nuclear reactors and nuclear weapons. Trace quantities also originate from spontaneous fission of uranium-238.
Cam	A cam is a rotating or sliding piece in a mechanical linkage used especially in transforming rotary motion into linear motion.
Carbon resistor	Carbon resistors are cheap general-purpose resistors used in electrical and electronic circuits. Their resistive element is manufactured from a mixture of finely ground carbon dust or graphite (similar to pencil lead) and a non-conducting ceramic (clay) powder to bind it all together.

Cathode	A cathode is an electrode from which a conventional current leaves a polarized electrical device.
Cathode bias resistor	The cathode bias resistor value is found by dividing the absolute value of the operating point grid voltage by the operating point cathode current (plate current plus screen current). The power dissipated by the cathode bias resistor is the product of the square of the cathode current and the resistance in ohms.
Cell manufacture	In cellular manufacturing, production workstations and equipment are arranged in a sequence that supports a smooth flow of materials and components through the production process with minimal transport or delay.
Circuit board	A thin, rigid board containing an electric circuit; a printed circuit.
Closed-loop (gain)	The gain of the amplifier with the feedback loop closed, as opposed to the open-loop gain, which is the gain with the feedback loop opened.
Computer-aided design	Computer-aided design is a means to digitally create 2D drawings and 3D models of products before manufacture. With CAD, designs can be shared, reviewed, simulated, and modified.
Continuous flow	Continuous-flow manufacturing, or repetitive-flow manufacturing, is an approach to discrete manufacturing that contrasts with batch production.
Copy milling	Copy milling is more commonly known as free-form milling. A copy is made of the object being milled.
Diffraction grating	In optics, a diffraction grating is an optical component with a periodic structure that diffracts light into several beams travelling in different directions (i.e. different diffraction angles).

Digital differential analyser	In computer graphics, a digital differential analyser (DDA) is hardware or software used for the interpolation of variables over an interval between start and end point.
Digital machine tool	A machine tool has a camshaft and indexing drive mechanism, which is driven by a servomotor and is therefore adapted for operation.
Diode	A diode is a two-terminal electronic component that conducts current primarily in one direction (asymmetric conductance); it has low (ideally zero) resistance in one direction, and high (ideally infinite) resistance in the other direction.
Distortion	The amplitudes of all frequencies within an amplifier's operating range must be amplified by the same factor to avoid distortion. An amplifier which satisfies this requirement is said to be perfectly linear. If the peaks of the waveform are clipped, this gives rise to what is called harmonic distortion. Another type of distortion is intermodulation distortion, which occurs when different frequencies in the signal mix to produce sum and difference frequencies which did not exist in the signal.
Double pinion	The double pinion allows for a smoother drilling action. The double pinion (gear) is connected to the main drive wheel in two places.
Drunken thread form	Thread with erratic pitch, in which the advance of the helix is irregular in one complete revolution of the thread.
EDM (electro-discharge machining)	A non-traditional form of precision machining that uses thermal energy instead of mechanical force.

Electrochemical machining (ECM)	A method of removing metal by electrolytic anodic dissolution. It is normally used for mass production and is used for working extremely hard materials or materials that are difficult to machine by conventional methods. Its use is limited to electrically conductive materials.
Electroforming	Electroforming is a metal forming process in which parts are fabricated through electrodeposition on a model, known in the industry as a mandrel.
Electrohydraulic control valve	Electrohydraulic valve actuators and hydraulic valve actuators convert fluid pressure into motion in response to a signal. They use an outside power source and receive signals that are measured in amperes, volts, or pressure. Hydraulic actuators can be used when a large amount of force is required to operate a valve.
Electrolytic bypass capacitor	It eliminates voltage drops on the power supply by storing electric charge to be released upon the occurrence of a voltage spike.
Electro-optical inspection	A contactless measuring technique, claimed to be 100 per cent reliable and fast in operation.
Feed-rate	Feed-rate is the velocity at which the cutter is fed, that is, advanced against the workpiece. It is expressed in units of distance per revolution for turning and boring (typically inches per revolution (ipr) or millimetres per revolution).
Feed screw mechanism	In machine tools, the mechanism used to construct the guide spindles and the support spindles.

Germanium diode	Germanium diodes were used in early electronics, such as radios, but they have largely been replaced by silicon diodes. It becomes a semiconductor when suitably doped with impurities.
Glass-filled nylon	Glass-filled nylon is created by adding powdered glass to the nylon resin or by extruding the plastic with glass fibres.
Grinding	A mechanical process using a rotating grinding wheel made from abrasive material containing small particles of grit ranging from fine to coarse. The wheel revolves around a central axis, making contact with the surface of the workpiece, while the particles act as cutting tools that cut chips from the material.
Group technology	A manufacturing technique in which parts having similarities in geometry, manufacturing process and/or functions are manufactured in one location using a small number of machines or processes.
Harmonic distortions	The production of frequency components, by circuit non-linearity, at integer multiples of the fundamental frequency passing through the circuit. For instance, clipping a sine wave to resemble a square wave will produce third, fifth and seventh, etc. harmonics.

Helical screw and pitch nut	A screw thread, often shortened to thread, is a helical structure used to convert between rotational and linear movement or force. A screw thread is a ridge wrapped around a cylinder or cone in the form of a helix, with the former being called a straight thread and the latter called a tapered thread. A screw thread is the essential feature of the screw as a simple machine and also as a threaded fastener. The mechanical advantage of a screw thread depends on its lead, which is the linear distance the screw travels in one revolution. In most applications, the lead of a screw thread is chosen so that friction is sufficient to prevent linear motion being converted to rotary, that is so the screw does not slip even when linear force is applied, as long as no external rotational force is present.
High-frequency induction motor	The main features are power, precision, direct mounting of the tool, and the construction of the shaft according to industrial applications.
Hydraulic motor	A mechanical actuator that converts hydraulic pressure and flow into torque and angular displacement (rotation). The hydraulic motor is the rotary counterpart of the hydraulic cylinder as a linear actuator.
Hydraulic servomechanism	It consists of the following hydraulic components: the hydraulic pump which delivers hydraulic energy, the servo system. The servo system consists of a servo-valve, hydraulic ducts, hydro-motor and the sensors for angular velocity and angle.

Hydrostatic bearing	Bearings in which the load is supported by a thin layer of rapidly moving pressurized liquid or gas between the bearing surfaces. Since there is no contact between the moving parts, there is no sliding friction, allowing fluid bearings to have lower friction, wear and vibration than many other types of bearings.
Impedance	An expression of the opposition that an electronic component, circuit, or system offers to alternating electric current. It is often expressed as the vector sum of a resistive component and reactive component.
Injection moulding	A forming process using moulds. Materials such as synthetic resins (plastics) are heated and melted, and then sent to the mould where they are cooled to form the designed shape. Due to the resemblance to the process of injecting fluids using a syringe, this process is called injection moulding.
Integrated flexible manufacturing system (FMS)	An Industrial Flexible Manufacturing System (FMS) consists of robots, Computer-controlled Machines, Computer Numerical Controlled machines (CNC), instrumentation devices, computers, sensors, and other stand-alone systems such as inspection machines.
Ion plating	Ion plating is a physical vapour deposition (PVD) process that utilizes concurrent or periodic bombardment of the substrate and depositing atoms of film material by atomic-sized energetic particles. The bombardment prior to deposition, sputter cleans the surface.
Kinkless tetrode output valve	A kinkless tetrode has the same number of grids as the conventional tetrode but without the negative resistance kink in the anode current vs anode voltage characteristic curves of a true tetrode.

KT66 valve	The KT66 is a very well-known audio output beam tetrode valve.
Lead screws	A lead screw is sometimes referred to as a “power screw” or a “translation screw”. They are used within motion control devices to transform rotary or turning movements into linear movements.
Lecher wire	A Lecher line or Lecher wires is a pair of parallel wires or rods that are used to measure the wavelength of radio waves, mainly at VHF, UHF and microwave frequencies.
Line counting	Line counting is based on the linear measurement is the distance between the two given points or objects. For example, the total gap measured between the leftmost and rightmost end of an object in the specified system of units.
Logic element	An electronic device that performs an elementary logic operation.
Logic system	A way of mechanically listing all the logical truths of some part of logic by means of the application of recursive rules—i.e., rules that can be repeatedly applied to their own output.
LP2 triode oscillator	LP2 is the name of the component. A triode is an electronic amplifying vacuum tube (or valve) consisting of three electrodes inside an evacuated glass envelope: a heated filament or cathode, a grid, and a plate (anode). Electronic oscillators using triode vacuum tube. An electronic oscillator is an electronic circuit that produces a periodic, oscillating electronic signal, often a sine wave or, a square wave or a triangle wave.

Machine tools	A machine for handling or machining metal or other rigid materials, usually by cutting, boring, grinding, shearing, or other forms of deformations. Machine tools employ some sort of tool that does the cutting or shaping.
Magnetic amplifier	A magnetic amplifier is an electromagnetic device that amplifies electrical signals utilizing a transformer's core saturation principle and the core non-linear property.
Magnetic tape	Magnetic tape is a medium for magnetic storage made of a thin, magnetisable coating on a long, narrow strip of plastic film.
Micro-miniature valve	A micro-mini valve (amplifier) is small enough to be portable and compact while still allowing enough amplification to be useful in certain applications.
Milling	Milling is the process of grinding, cutting, pressing, or crushing a material in a special machine. Milling is the process of cutting away material by feeding a workpiece past a rotating cutter with many teeth.
Moiré fringe effect	Large-scale interference patterns that can be produced when an opaque ruled pattern with transparent gaps is overlaid on another similar pattern. For the moiré interference pattern to appear, the two patterns must not be completely identical, but rather displaced, rotated, or have a slightly different pitch.

Multi-cellular manufacturing	Cellular manufacturing involves the use of multiple “cells” in an assembly line fashion. Each of these cells is composed of one or multiple different machines which accomplish a certain task. The product moves from one cell to the next, each station completing part of the manufacturing process.
Negative feedback	A negative-feedback amplifier (or feedback amplifier) is an electronic amplifier that subtracts a fraction of its output from its input, so that negative feedback opposes the original signal.
Non–polar capacitor	A non-polarized (“non-polar”) capacitor is one that has no implicit polarity and can be used in either direction in a circuit.
Numerical control (NC)	Numerical control (also computer numerical control, commonly called CNC) is the automated control of machining tools (such as drills, lathes, mills, grinders, routers and 3D printers) by means of a computer.
Optical interference grating	When light encounters an entire array of identical, equally-spaced slits, called a diffraction grating, the bright fringes, which come from constructive interference of the light waves from different slits, are found at the same angles if there are only two slits. However, the pattern is much sharper.
Pallet	A pallet (also called a skid) is a flat transport structure which supports goods in a stable fashion while being lifted by a forklift, a pallet jack, a front loader, a jacking device, or an erect crane.
Pelton wheel	The Pelton wheel or turbine extracts energy from the impulse of moving water.

Phase rotation	Phase rotation, or phase sequence, is the order in which the voltage waveforms of a polyphase AC source reach their respective peaks.
Photo-diode	A light-sensitive semiconductor diode. It produces current when it absorbs photons.
Photoelectric cell	Photoelectric cell, also called Electric Eye, Photocell, or Phototube, an electron tube with a photosensitive cathode that emits electrons when illuminated and an anode for collecting the emitted electrons.
Photo-sensitive device	A device that is responsive to electromagnetic radiation in the visible, infrared, and/or ultraviolet spectral regions.
Pickup	A stylus touches the top of the record and rides around the disk. It picks up vibrations that are then sent to a cartridge, which then converts them into electrical signals. These signals are sent to an amplifier, which converts the signals back to sound through speakers.
Plasma nitriding	Plasma nitriding is a method of surface modification using a glow discharge technology to introduce nitrogen into the surface of a metal, which subsequently diffuses into the material.
Positioning table	Positioning tables are apparatus used in power transmission to achieve a high-precision linear motion.
Power amplifier	A power amplifier is an electronic amplifier designed to increase the magnitude of power of a given input signal.

Press tools	Press tools are commonly used in hydraulic, pneumatic, and mechanical presses to produce the sheet metal components in large volumes. Generally, press tools are categorized by the types of operation performed using the tool, such as blanking, piercing, bending, forming, forging, and trimming.
Pressure die casting	A means of mass-producing low-temperature metallic components with a high degree of precision and repeatability. Unlike gravity die casting, the process is automated and the liquid metal or alloy is injected under high force into a hardened steel tool.
Pulse train	A pulse wave or pulse train is a type of non-sinusoidal waveform that includes square waves and similarly periodic but asymmetrical waves.
Punched tape	Punched tape or perforated paper tape is a form of data storage that consists of a long strip of paper in which holes are punched.
Push-pull output stage	A push–pull amplifier is a type of electronic circuit that uses a pair of active devices that alternately supply current to, or absorb current from, a connected load. This kind of amplifier can enhance both the load capacity and switching speed.
Rack and pinion	The rack and pinion type steering mechanism consists of a pinion attached to the tip of the steering shaft on which the steering wheel is mounted. The pinion is meshed with a rack so that the movement of the handle rotates the pinion, which in turn moves the rack sideways.

Receiver valve, transmitting valve	Valves are high voltage / low current devices in comparison with transistors. Tetrode and pentode valves have very flat anode current vs. anode voltage, indicating high anode output impedances. Triodes show a stronger relationship between anode voltage and anode current.
Recirculating ball screws	Recirculating ball screw is the mechanical component used in movement transmission, used to transform a rotary motion into a translational motion. This mechanical component is precise and offers superior performance.
Reinforced plastic	A fibre-reinforced polymer (FRP) is a composite material consisting of a polymer matrix embedded with high-strength fibres, such as glass, aramid, and carbon.
Routing head	A tool used to hollow out or cut grooves. It is composed of motor and router parts.
Screen printing	Screen printing (traditionally called silkscreen printing; also known as serigraphy and serigraph printing) is a printing technique where a mesh is used to transfer ink (or dye) onto a substrate, except in areas made impermeable to the ink by a blocking stencil.
Screw transmission	The screw-nut transmission is a machine element that consists of the combination of a screw and a nut and is used for power transmission.
Servomechanism	A powered mechanism, producing motion or forces at a higher level of energy than the input level.
Signal distortion	In signal processing, distortion is the alteration of the original shape (or other characteristic) of a signal.
Silicon crystal	Silicon crystal, mainly in monocrystalline form, are used in the production of microchips.

Sinusoid and quadrature	In electrical engineering, a sinusoid with angle modulation can be decomposed into, or synthesized from, two amplitude-modulated sinusoids that are offset in phase by one-quarter cycle (90 degrees or $\pi/2$ radians). All three functions have the same centre frequency. Such amplitude-modulated sinusoids are known as the in-phase and quadrature components.
Slideway friction	The friction and wear behaviour of machine tool slideways is assessed against the background of materials being used.
Slideways	Used as the medium on which to slide heavy equipment. This type of system is used when the equipment to be transported is either very heavy or when the movement requires high precision.
Small batch manufacture	Small batch production is the term used when a production run is for less than 500 units.
Spindle speed	It is the rotational frequency of the spindle of the machine, measured in revolutions per minute (RPM). The preferred speed is determined by working backward from the desired surface speed (sfm or m/min) and incorporating the diameter (of workpiece or cutter).
Split-pinion	The split-pinion method uses two pinion halves, which mesh with opposite tooth flanks on the same rack. One half of the pinion is driven, and the other half is preloaded with an axial spring pack, which compensates for backlash. In a split-pinion design, one pinion drives the system and the other is preloaded.
Spring-loading mechanism	An object or mechanism is held tightly against a spring, but is initially 'locked' into position. Once 'unlocked', the object or mechanism is propelled out by the natural action of the spring.

Stylus	Turntable needle housed within a cartridge. The needle, better known as the stylus is the part that physically touches the surface of the vinyl record. The needle tracks the grooves and is normally made of a tiny gemstone or polished diamond.
Superplastic forming	Superplastic forming is a specialist process used for deforming metal sheet to extremely large plastic strains to produce thin-walled components to the near-net shape. Stretching of the sheet during superplastic forming is much higher than with rolling and sheet forming.
Surface finish	The nature of a surface as defined by the three characteristics of lay, surface roughness, and waviness. It comprises the small, local deviations of a surface from the perfectly flat ideal (a true plane).
SYSTEM 24	The first-ever integrated computer-controlled system of batch manufacture.
Thermocouple	A thermocouple is an electrical device consisting of two dissimilar electrical conductors forming an electrical junction. A thermocouple produces a temperature-dependent voltage as a result of the Seebeck effect, and this voltage can be interpreted to measure temperature.
Thread angle	The angle between the 'thread flanks', the two straight surfaces from root to crest. In other words, it is the angle of the 'V' of the thread form.
Tolerance	Engineering tolerance is the permissible limit or limits of variation in: a physical dimension; a measured value or physical property of a material, manufactured object, system, or service; other measured values (such as temperature, humidity, etc.);

Transistor	A transistor can act as a switch or gate for electronic signals, opening and closing an electronic gate many times per second. It ensures the circuit is on if the current is flowing and switched off if it is not. Transistors are used in complex switching circuits that comprise all modern telecommunications systems. Also when biased in its linear region can be used as an amplifying device.
Triode amplifier valve	A triode is an electronic amplifying vacuum tube (or valve) consisting of three electrodes inside an evacuated glass envelope: a heated filament or cathode, a grid, and a plate (anode).
Twin spindle milling	Milling spindles, as the main spindle of tool machines, are responsible for machine cutting a workpiece.
Two-phase electrical power	Two-phase electrical power was an early 20th-century polyphase alternating current electric power distribution system. Two circuits were used, with voltage phases differing by one-quarter of a cycle, 90°.
UHF	UHF (ultrahigh frequency) defined portion of the electromagnetic spectrum, encompassing radiations having a wavelength between 1m and 1 dm and a frequency between 300 megahertz and 3 gigahertz.
Vacuum carburizing	Vacuum carburizing (or LPC-Low Pressure Carburizing) is a process where the parts are heated up, and then carburizing gases are added under an absolute pressure of a few mbar. Carburizing gas is acetylene (hydro-carbon), where the steel will absorb the carbon and create a layer of hard metal called the case.

Vector direction	The direction of a vector is the orientation of the vector, that is, the angle it makes with the x-axis.
Velodyne	A device in which the output of a tacho generator is fed back so as to keep the rotational speed of a shaft proportional to an applied voltage.
VHF	Very high frequency (VHF) is the ITU (International Telecommunication Union) designation for the range of radio frequency electromagnetic waves (radio waves) from 30 to 300 megahertz (MHz), with corresponding wavelengths of ten metres to one metre.
Waveguide	A structure that guides waves, such as electromagnetic waves or sound, with minimal loss of energy by restricting the transmission of energy to one direction.

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